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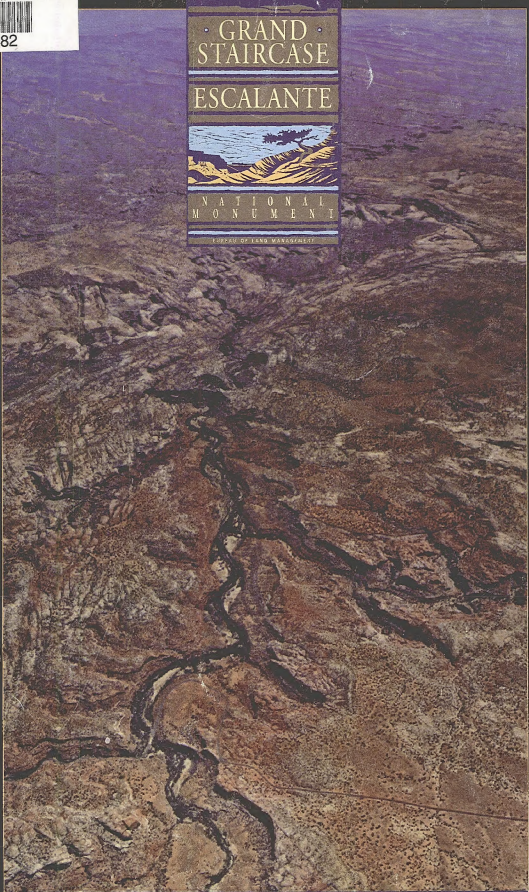
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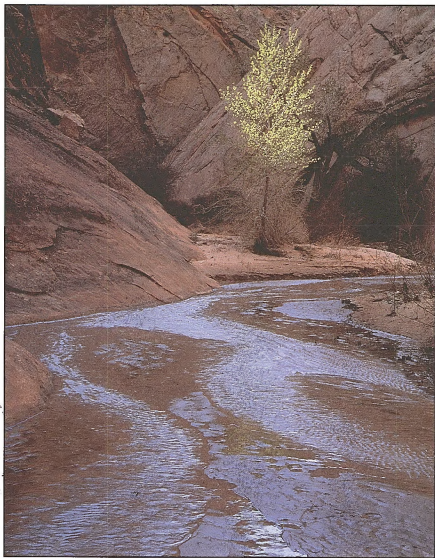
U.S. DEPARTMENT OF LAND MANAGEMENT



Learning from the Land

*Grand Staircase-Escalante National Monument
Science Symposium Proceedings 1997*

Southern Utah University Hunter Conference Center, Cedar City, Utah



Cottonwood tree in Hackberry Canyon.

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LEARNING FROM THE LAND



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Learning from the Land

Grand Staircase-Escalante National Monument Science Symposium Proceedings

November 4-5, 1997
Southern Utah University

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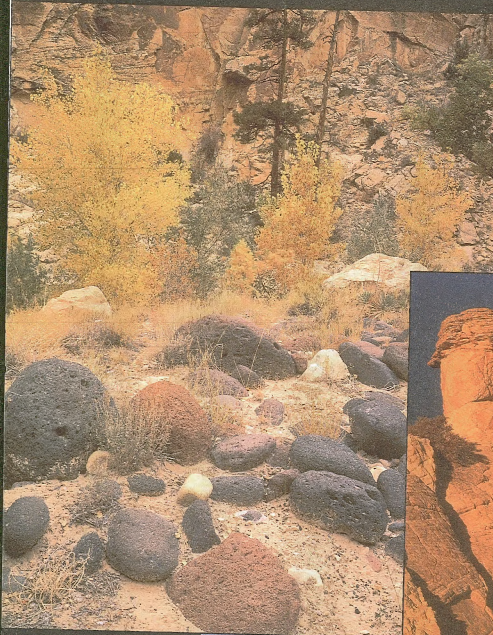
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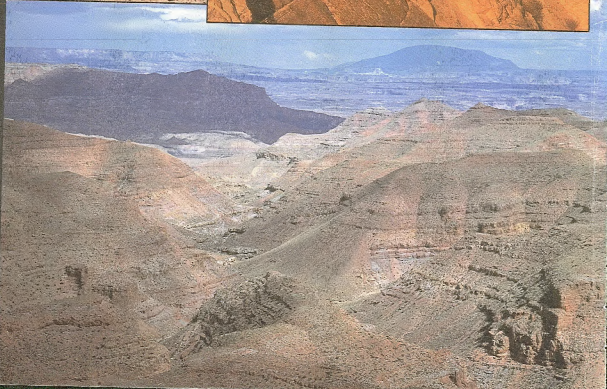
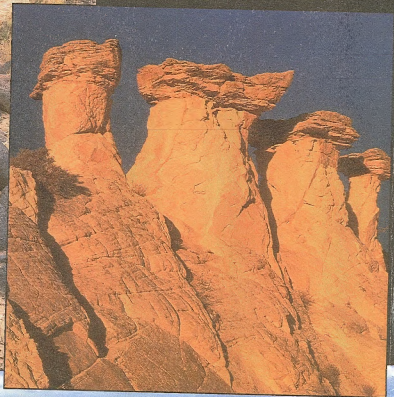
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Left: Boulders and cottonwood trees in Escalante River Canyon in autumn.

Below: Navajo sandstone hoodoos with caprock near Escalante River.

Bottom: Burning Hills area looking towards Navajo Mountain



Acknowledgments

The Bureau of Land Management (BLM) would like to express its appreciation to all who participated in the *Learning from the Land* science symposium. Thanks go to those who took the time to prepare and make presentations, as well as to those who attended the sessions. Special recognition goes to Utah Governor Michael O. Leavitt and Secretary of the Interior Bruce E. Babbitt for their personal interest, attendance, and remarks.

The symposium would not have been a success without the involvement and support of various organizations. BLM especially thanks Southern Utah University (the Hunter Conference Center and the Center for Rural Life), Paragon Press, Utah State Advisory Council on Science and Technology, Utah Division of Wildlife Resources, and Utah Geological Survey.

A number of individuals performed specific tasks to make the symposium happen. We would like to thank the members of the Steering Committee:

Suzanne Winters - Utah State Science Advisor
Rob Hellie - BLM Washington Office
Marietta Eaton - BLM Grand Staircase-Escalante National Monument
Thomas Slater - BLM Utah State Office
William Wagner - BLM Utah State Office

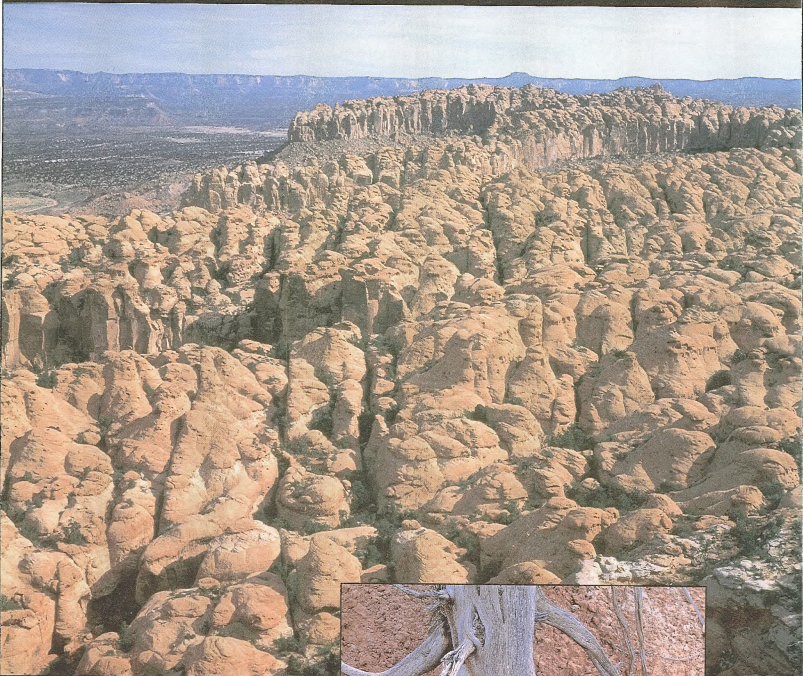
We would also like to recognize the following subcommittee chairpersons:

Terry Sharik - Utah State University
Virginia Ord - Davis County School District
M. Lee Allison - Utah Geological Survey
Patti Frampton MaGann - Utah Division of Wildlife Resources
Kezia Nielsen - BLM Grand Staircase-Escalante National Monument
Suzanne Garcia - BLM Utah State Office
Cheryl Johnson - BLM Utah State Office

In addition, many other people provided valuable assistance as subcommittee members and field trip hosts, and with conference registration and other activities. Our sincere appreciation and thanks go to each one of you for your hard work.



Calf Creek in winter.



Above: Wolverine Bench area.

**Right: Firecracker penstemon
and juniper snag near
Cottonwood Canyon Road.**





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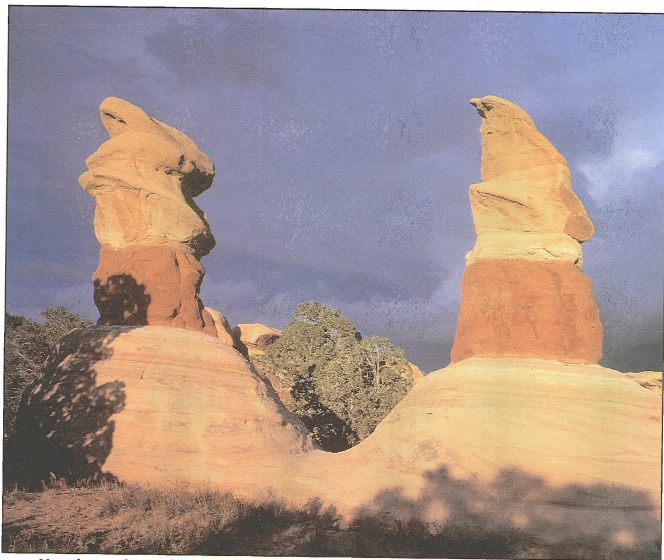
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Navajo sandstone hoodoos in Devil's Garden.



Introduction

"The Grand Staircase-Escalante National Monument's vast and austere landscape embraces a spectacular array of scientific and historic resources. This high, rugged, and remote region, where bold plateaus and multi-hued cliffs run for distances that defy human perspective, was the last place in the continental United States to be mapped. Even today, this unspoiled natural area remains a frontier, a quality that greatly enhances the monument's value for scientific study. The monument has a long and dignified human history: it is a place where one can see how nature shapes human endeavors in the American West, where distance and aridity have been pitted against our dreams and courage. The monument presents exemplary opportunities for geologists, paleontologists, archeologists, historians, and biologists."

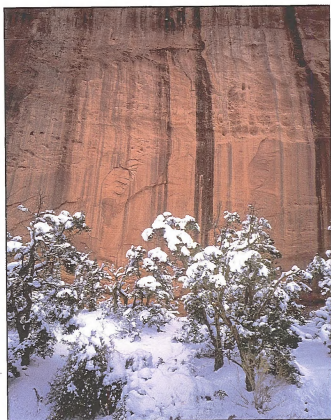
*Presidential Proclamation 6920
September 18, 1996*

The Grand Staircase-Escalante National Monument was created by Presidential Proclamation to protect almost 2 million acres of rugged and primitive land in the Colorado Plateau (see map inside back cover). The Monument contains three distinct regions—the Grand Staircase, the Kaiparowits Plateau, and the Escalante Canyons—each with its own unique attributes. Within the Monument's boundaries lie a vast array of remarkable geological, paleontological, archaeological, biological, and historic features. The scientific value of some of these resources is well-known; for others, it is yet to be discovered.

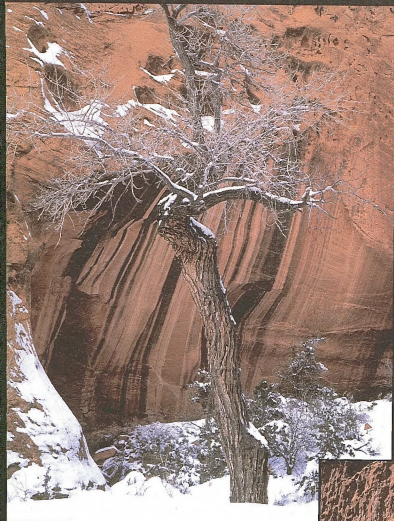
In an effort to better understand the level of existing knowledge and to explore the scientific potential of the Monument, a scientific symposium was held in November of 1997. The *Learning from the Land* science symposium was sponsored jointly by the Grand

Staircase-Escalante National Monument, the State of Utah, and Southern Utah University. The symposium was designed to provide a venue for scientists and managers to discuss the natural sciences and projects that have been conducted in the Monument or have application to the Monument.

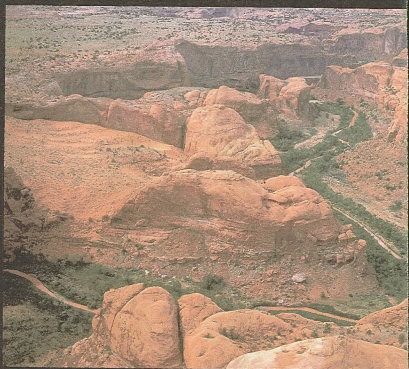
The interdisciplinary collection of scientific papers in this volume represents the first anthology of writings specifically related to the Grand Staircase-Escalante National Monument. They show the great range of scientific interest and expansive potential of knowledge waiting to be discovered. This volume represents the first step in cooperation between scientists and managers working toward the realization of the scientific promise of the Grand Staircase-Escalante National Monument.



**Wall streaking on Navajo sandstone
behind snow covered pinyon and juniper
trees in Long Canyon.**

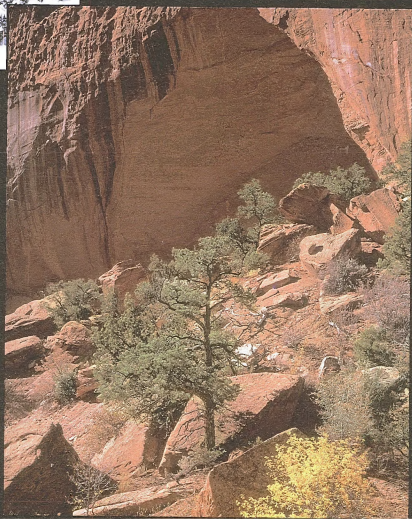


Above left: Winter snow blanketing a cottonwood and the Navajo Sandstone in Long Canyon.

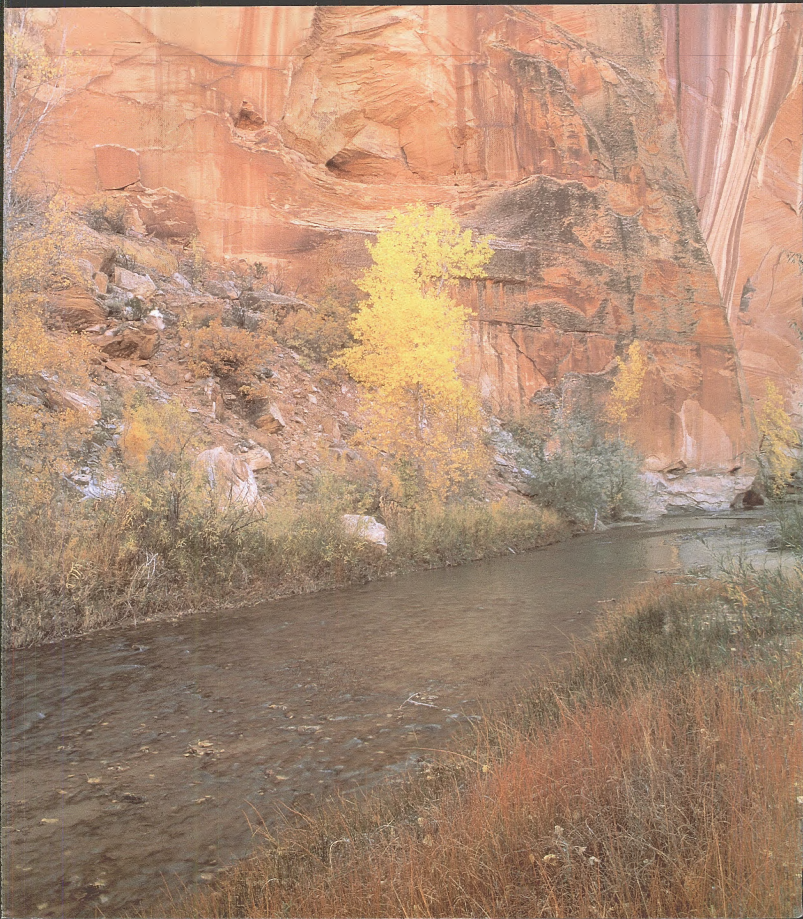


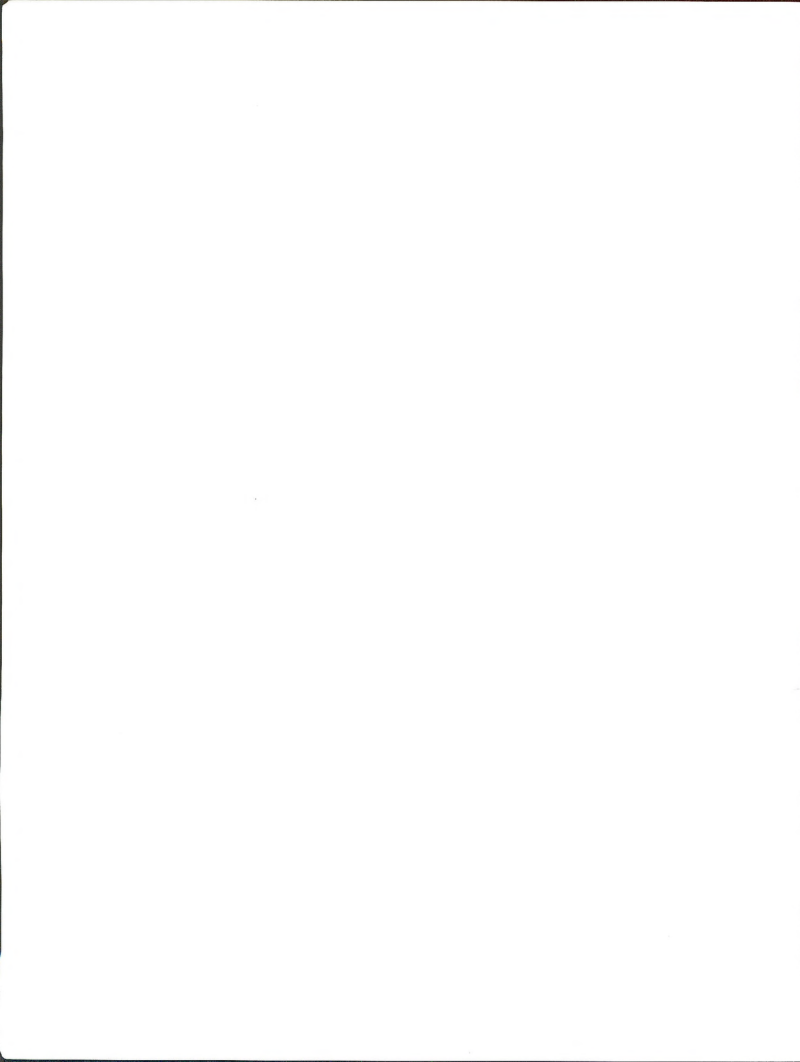
Above right: Escalante River area.

Right: Juniper and Navajo Sandstone in Long Canyon.



WELCOME







Jerry Meredith Manager, Grand Staircase- Escalante National Monument

On behalf of the employees of the Grand Staircase-Escalante National Monument, and particularly the members of the planning team, we want to issue a special welcome to all of you who have joined us today. We consider this a very exciting opportunity for the Bureau of Land Management as a whole, and for those of us who have been assigned to work at the National Monument in particular.

This is the first such science symposium for the new National Monument, but we certainly hope it isn't the last. The President's Proclamation specifically stated that, and I quote, "The Monument presents exemplary opportunities for geologists, paleontologists, archeologists, historians, and biologists." And we, as the members of the planning team, intend to make sure that opportunity continues to be present and continues to expand.

Many of us who have worked in this area of southern Utah for a lot of years have known for a long time that this is a special area with a great deal of exciting and unique scientific opportunities. But we'll also be the first ones to admit that there is more that we don't know than there is that we do know. There's a long way to go and we're excited about beginning down that road. Much has been said in recent years about the importance of using good science in land management, and for those of us whose job it is to manage the public's land heritage, this has always been something that's been an important goal for us.

There are two required elements before that goal can become a reality. First of all, managers

need to communicate clearly to researchers the types of research they need. Then they need to help make that research possible by providing local support and assisting with

funding. Researchers have responsibilities also. They need to translate their work into easily understood language; after all, managers aren't the brightest people around. We need all the help we can get. They also need to help make certain their research is relevant to today's challenges. In other words, they need to answer the "So what?" question without waiting to be asked.

Those of us who work at the Grand Staircase-Escalante want to do our part towards making both of these elements a reality. We want to make this a science-friendly Monument where it's easy to do work and easy to provide opportunities for those who are in the business of doing scientific research. We also want to hold up our end of the responsibility in clearly communicating our needs and in making sure that the work that is done is put to good use on the ground.

This symposium is the first step on that road; it will be a long road and a continuous road. Not a destination, but a journey, and we appreciate each one of you for being here today to help us take the first step down that road. We'd especially like to thank our partners





in this symposium; we certainly couldn't have held a symposium of this magnitude without them. Our partners in the symposium are Southern Utah University and the State of

Utah Advisory Council for Science and Technology.

Thank you very much.



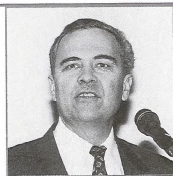
Dr. Steve Bennion President, Southern Utah State University

We're honored to have you on our campus today, and on behalf of the University, extend a warm welcome to all of you. I think it's exciting on this historic occasion to have you here, to come and reason together on opportunities that are facing the nation, but also particularly this part of the nation, as we look ahead at our precious national resources.

This is a remarkable year at the University; the hall you're in is called the Great Hall—it used to be a gymnasium years ago. Some of the wonderful people in the history of the University are pictured on the wall. I'll embarrass the Governor for a moment—the fourth portrait over is his father, Dixie Leavitt. But there are many wonderful people who've helped us in this hundred-year history to bring us to where we are today. I see in the audience members of our faculty; we have a wonderful faculty at this institution and several of our science faculty are here today. Some have been working very actively on this project—Professor Richard Dotson and others—and I salute them for their interest in this important area. We are a regional university; we have about 6,000 students. In a hundred years much has happened, and I think perhaps the most important thing that happened this year was the writing of the wonderful history of the institution. In case any of you are history buffs, it's for sale in our book store. I should also tell you that the author of this history is Anne Leavitt, the Governor's mother. The Governor is also a distinguished alumnus of this institution and we're certainly proud of that connection. We are pleased today to also

welcome to our campus Mr. Bruce Babbitt, Secretary of the Interior.

Six months ago we had the grand celebration of the centennial. Besides the Governor of the State of Utah, former President George Bush, President Gordon B. Hinkley of the LDS Church, Dr. Michael DeBakey, the one who pioneered open heart surgery, Dr. C. Everett Koop, a very well-known Surgeon General of the United States, David Scott, one of the first astronauts on the moon, and the Secretary of Education from Russia in Yeltsin's current cabinet all came. It was a very impressive day. I was the President Elect; I did not plan all of that, I just came to enjoy it. But it was a great day to celebrate this University and its history.




I know that you have come together in a spirit of "let's reason together." I'm sure there are many different viewpoints on this development that has occurred. I do think it's great though to live in a land where we can come and reason together and respect those different viewpoints. We are very close, as you undoubtedly know, to many of the national resources, Parks, Monuments, right here in Cedar City. The Cedar Breaks National Monument's a half-hour drive, Zion National Park is probably about an hour away, the Bryce Canyon National Park is a 70-minute drive, 2 hours drive to the Grand Canyon, and now, the Grand Staircase-Escalante National



Monument being an hour and a half. These are all important efforts that have been made by our Government in behalf of the people, that we can enjoy what nature has provided. Much has been done to preserve these resources and I salute that effort.

When I was writing my senior thesis, as an undergraduate student in political science, I had an interest experience. I wrote about the politics of a county in eastern Utah and that was the area where my uncle and another man initiated a major effort to develop the upper Colorado River Project. That represents another side of the issue, but they worked much through the early 1950's to get that proposal

through Congress. And in one of the Congressional hearings, an interesting thing happened; the curator of the Dinosaur National Museum in Vernal was testifying. He was obviously advocating the development of the upper Colorado River Project. There were some who were taking an opposite position and he referred to their genuine concerns and he said, "I know they want to save us, but we don't want to be saved, we want to be dammed." Now I hope it's in that good spirit of understanding differences of opinion that you come here today. Again, we're honored to have you on our campus at Southern Utah University.





Michael Leavitt

Governor, State of Utah

Good morning. It's a privilege to be with you. As you will suspect from the earlier introductions, this is a place I come to by choice. It's really my home. I remember when this was a gym; in fact, I remember as a very small boy, my parents, both of whom have been represented today as having quite a bit of attachment to this area and school, were here as a young married couple. I must have been 4 or 5 years old because I remember just learning to dribble a basketball and my father lifting me up in this very spot where I could throw the ball into the hoop. I remember with some vividness that experience.

As you walk around this campus and as you walk around this town, you will see a rather marked effort to have the entire surroundings reflect the natural beauty of the area. If you stand outside this building, you will see that beautiful red mountain, as you drive up this canyon you'll see Cedar Breaks, as you go to Zion and all of the National Parks. You'll see it in the colors of the buildings, you'll see it in the design of the buildings, and you'll see it in the way people landscape their yards. This is an area that is devoted to a sense of natural beauty and we love it. We love it.

About 3 years ago, I remember meeting with Secretary Babbitt at the University Park Hotel in Salt Lake City. Bruce, I don't know if you'll remember this meeting, but I laid out for the Secretary a kind of grand scheme I had in my mind that had come after a long discussion with a number of Federal, State, and local land managers. It was an idea of how we could bring together a lot of different problems in this area which is the subject of your study. We could call it the Grand Staircase or

Canyons of the Escalante and National Eco-Region. Basically, the idea was to create a single management philosophy that could pervade this entire area even though we were going to be part of different agencies. Actually, that was the first time I ever heard the word "monument" used. The Secretary said, "Let me talk to you about the idea of a monument." It didn't mean much to me at the time, but it does now. I guess I should have been listening better. But the point is that people in this area, in our State, and people around the world want to protect this land. This is land we love, and these are places that we grew up. This is really a big part of our lives.

The proposal did not succeed for a lot of different reasons. About 2 years later, by a process that has been controversial and on which there has been lots said, and I've said my part, the National Monument that we study today was created. After it had been created by Proclamation, I made a policy decision on the part of the State that, as much as I didn't like the way it happened, my commitment was to protect the land and to create a model of environmental management in that area that could succeed in protecting the land. I made a commitment on the part of the State that if the Federal government would come to the table and involve us in the process, we would bring smart people and money to the table to help. And to their credit, they have done that and I believe to ours, we have done





that also. We now have a planning team in place that has been working for almost a year, and we're making good progress. This symposium is part of that effort.

Now, I want to make just one reflection on a general basis. I've been involved in public policy now and as a policymaker for almost 5 years. One of the most frustrating aspects of this to me has been one phrase or one thought. People continue to ask me, "Why is it that you politicians ignore the science in developing public policy?" The frustration I feel is the question: "Whose science?" because, as a policymaker, I am constantly having scientists of general, good reputes give me different points of view. I have come to find out that all scientists do not agree; that it's not something that is absolute, and there are people of a substantial sincerity and enormous credential who see the world differently. So, when you're in a public policymaking role and you follow one science, there is always another science that disputes what you've said.

I've also come to find out that there are different languages we use. Sometimes, scientists use different words than planners do, and both

of them use a different language than public policymakers do. Now, I believe very strongly, that in the context of this discussion, there is a common goal. That goal is to preserve the land and to do it in a way that is responsible.

So, I plead with you today, during this conference, to accomplish a few things: 1) do what you can to bring the science together to where science is speaking not just with one voice, but with one language, and 2) move forward with a sense of conciliation, with a desire to protect the land. Because I am convinced that if we do that, we can in fact, accomplish what our goal has been from the very beginning, and that is to create a model of environmental management in an area of the world that has the most spectacular land I know of that God created. The State of Utah continues to be committed to this. We want very much to preserve this, to protect it, and to create a model of environmental management. I continue to pledge our efforts to do so and look forward to working with you and seeing the outcome of your symposium.

Thank you.





Bruce Babbitt

Secretary of the Interior

Learning from the Land: Scientific Inquiry for Planning and Managing the Grand Staircase- Escalante National Monument

Thank you, Jerry. Good morning. I'm pleased to be here. As I listened to Jerry's introduction, I must confess to you that I come before a group of scientists with a certain deep nostalgia.

As you heard in Jerry's introduction, I once aspired to be a scientist. I got an undergraduate degree in geology, had the good fortune to get a scholarship to go abroad to study geophysics, and everything seemed to be unfolding rather nicely. But then, in the course of working, doing research on a thesis project, I began to have my doubts. I remember going home one particularly frustrating, late night after a bunch of laboratory experiments had crashed, and thinking to myself, as I suppose, all of us do at times during our careers, that I'd better take stock of myself, and the bottom line is I'm not smart enough to do this kind of work. And I better get out of here while there's still time and get into a softer line of work. So I applied to law school.

Well, be that as it may, I am delighted to be back on this campus. I've been here many times and each time as I come back to this extraordinary landscape, to this City and this Institution, I am convinced that there is

growing here in this community a really powerful commitment to the natural sciences. That commitment is firmly rooted in the appreciation and interpretation and elaboration of this extraordinary landscape, which is bracketed by all of the State and Federal land management units of which Dr. Bennion spoke. I applaud your work. For it recognizes that out here there is a very powerful vision of a future, which is rooted in knowledge, learning, and our understanding of this landscape.



I guess it's time to acknowledge the Governor of Utah. I do this with extraordinary pleasure because I must simply say to you (at the risk of tarnishing his reputation) that I consider the Governor of Utah to be one of my great and good friends and colleagues. Mike Leavitt has brought extraordinary skills to the conduct of what is, I think, universally acknowledged to be a very difficult job: being a Western Governor. He has worked on these resource issues with extraordinary skill and insight, manifest by our presence here today in a working relationship with the State of Utah.

I think I could readily agree with the Governor that we have different positions on a significant number of issues. But it has never impeded our ability to work together in a lot of areas where the future can provide enormous benefits for all of us. So, it's with real gratitude that I acknowledge the State of Utah's presence in this planning exercise for the Grand Staircase-Escalante National Monument.



I'd like briefly to just make a few points to you, first about the science that we deploy here today, and secondly about the relevance of this work product to the future, not just of this National Monument, but of entire region of Southern Utah and of the Colorado Plateau. I believe we're going to look back at this meeting today as a genuine milestone in the evolution of land management in the American West.

I believe in many ways this is, if not the first, the most striking example of a gathering which is dedicated to multidisciplinary science, crossing agency lines and deployed across a large landscape or ecosystem. All of us here are starting to appreciate the momentous nature of this transition.

Those of us in geology, anthropology, archeology, biology, and the social sciences would readily acknowledge that for many generations we have tended to see science in pieces rather than in its integrated whole. The times we live in, particularly out on the American landscape, so many problems press in on us. Demands over how to use resources escalate to unbelievable heights. The empty spaces are beginning to fill in. So we can no longer deploy science productively one discipline at a time.

The barriers are of necessity beginning to fade away. You can see it in universities where the old scientific disciplines are now beginning to be recast in multidisciplinary science form. You can see it within my own agency where the sciences have now been gathered together in one science agency. You can see it across the Federal Government with these large science projects addressing entire ecosystems like the Florida Everglades, the Yellowstone watershed, the Bay Delta of California, and the Pacific Northwest forests. In order to do that on this landscape at the very beginning, in order to lay down a baseline and to define the conditions by which we embark upon this adventure, we must embrace this extraordinary opportunity and utilize it to the fullest.

Now, if we use multidisciplinary science, if we successfully erase those agency lines—not just in the Federal government but in State government—and if we bring our university partners full bore into this partnership, that leaves simply the landscape itself, the object of our attention. We come today looking at the Grand Staircase-Escalante National Monument. But we're looking at more than that. We're not looking at a place grounded by lines on a map, we are looking at a system which encompasses the hydrology, the landscape, the life forms, the human history of this entire, extraordinary region.

Lastly, let me offer just a few thoughts about our role in the creation of the Grand Staircase-Escalante National Monument and a tentative vision that I think is already emerging about what this landscape should look like.

I think most of us—in State, Federal, local governments, all of us—are beginning to understand that this ought to be a different kind of place. This planning exercise contemplates a different vision. What do I mean by that? Let me explain by contrast.

Consider the creation of Grand Canyon, of Zion, of Bryce, all of the National Parks that this region is identified with. I'd be the first to acknowledge that those National Parks were created as Federal enclaves, in which people in Washington invited the Union Pacific Railroad to go down there, put up overnight a bunch of facilities right in the middle of the Federal enclave, go out, advertise across the world to bring people in, move them in quick, as if Utah did not exist, plunk them down in the middle of the Park, sell them a few postcards, a few T-shirts, and move them on to the next Park down the line.

In retrospect we now see that we can do better. We can begin to recognize that these landscapes are part and parcel of the history and the context and the culture and the communities that they're placed in. We can see that in this case, we are administering these assets in the context of one of the richest, historic traditions that's ever grown up in the United



States or anywhere else. People in this region do live lightly on the land.

Anyone who has ever on a summer day approached a Southern Utah town across a rural road, when you first see the Lombardi poplars on the horizon in those wonderful straight lines, drives into a community or village on these wide roads with the irrigation ditches bubbling through the town surrounded by agricultural fields at a human scale being tended, one family at a time, in the context of a community whose institutions, whose values and beliefs, have been conditioned deeply by their history, their leadership, their love of and their relation to that landscape. They will forever after hold a profound respect for the stewards who have lived for generations on this landscape and who have by their wisdom and innovation adapted to the reality of this landscape.

If you accept that characterization, as you must, it seems to me that our planning process for the National Monument immediately must reach out to those communities. You begin to draw some very obvious conclusions that a vision of this landscape should root to the extent possible the visitor in the total experience and history and culture and reality of this landscape.

This should not be an experience where you are brought in, encapsulated in a train or a bus or an airplane, plunked down in the midst of a national concessionaire sitting out in the midst of this scenery, and be expected to buy a few postcards and marvel at the sunset. The experience ought to begin with a deeper appreciation of the land. To the extent that communities want it, and I believe they do,

facilities should be available to provide interpretation, science, and all the normal amenities. But these should grow out of the rootedness of those communities, whether it's Escalante or Kanab or Tropic or Cedar City. We should turn to those communities to define the infrastructure and to deploy as many of their resources as we possibly can. The scientific capability of the local University, the facilities, the knowledge, the manpower, can all work together toward an entire interpretative experience. We have a chance to implement that kind of scenario or perhaps modifications that we haven't even thought of.

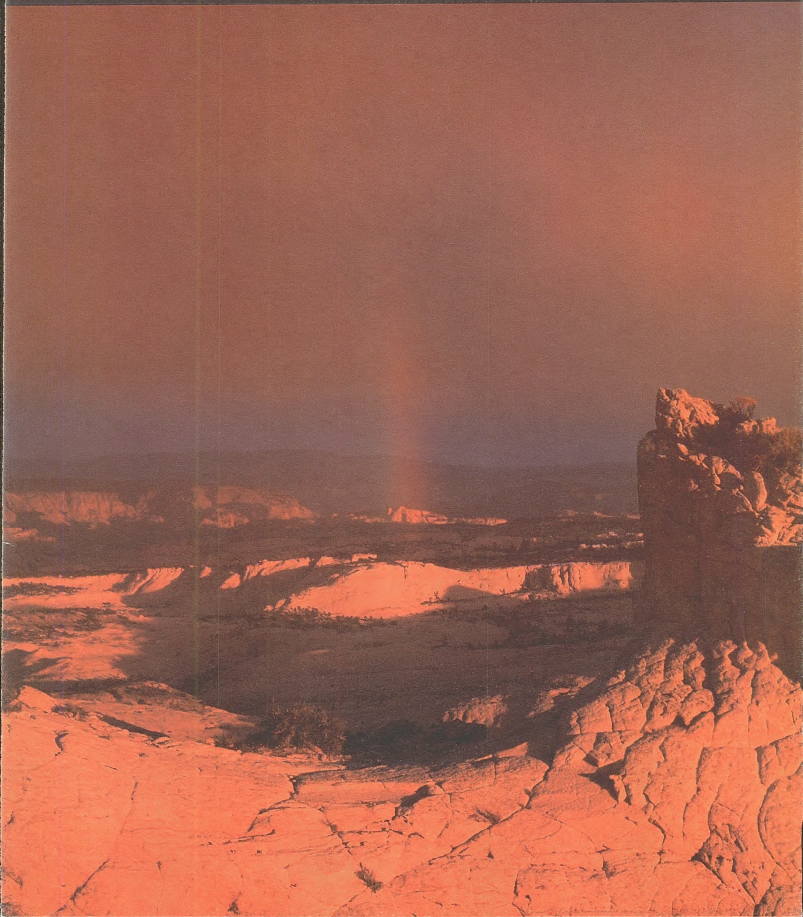
But one thing I am certain of is that—for perhaps the very first time in the history of Federal land management—we can and should begin this process with a powerful interdisciplinary and interagency examination of the landscape, of the ecosystem, of its capacities, of its baseline conditions, of its instructive history, and most of all, how we bring together and protect this extraordinary example of creation.

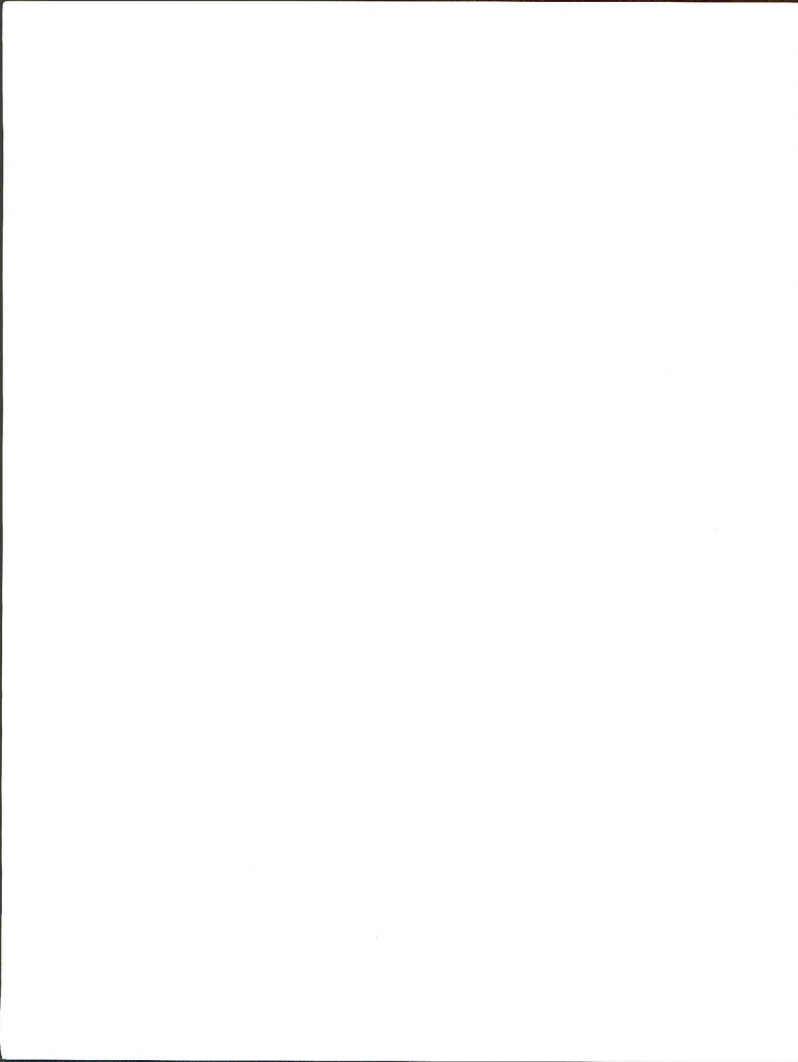
How do we do it? Together, in partnership with the people who are rooted on this landscape, we can turn and offer an extraordinary instructive experience in a new kind of way to people who want to see a little more, who want to learn a little science, who want to think about the incredible history of this landscape consecrated by generations of people rooted in this landscape. We'll have something very different and we'll be able some day to look back and say, "Maybe it really began right here."

Thank you very much. ■



PERSPECTIVES







Ecological Resources of the Grand Staircase-Escalante National Monument

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ABSTRACT

■ The Antiquities Act of 1906 gives the President of the United States the power to set aside areas of outstanding scientific interest, with the caveat that these areas be the minimum necessary to protect the identified objects of interest. This paper will address the following questions: What objects of biological interest are found in the Grand Staircase-Escalante National Monument? Why they are they unique or of interest to scientists and the public? What is the minimum area required to protect their scientific value?

What Is of Scientific Interest in this Area?

Wildlife

The Monument is home to approximately 300 species of amphibians, birds, mammals, and reptiles. This diverse set of wildlife species includes over 20 species of birds of prey such as the bald eagle and the peregrine falcon. The Monument is also within the historical range of the condor. This region contains two of the seven recognized centers of endemism for fishes of the western United States (Davidson et al., 1996). Successful reintroduction of bighorn sheep, Rocky Mountain elk, and Miriam and Grand turkeys have added to the biodiversity found here. Over 360 km of streams in the Monument add greatly to the value of this area as wildlife habitat (F.C. Jensen, pers. comm.; Utah Wilderness Coalition, 1990).

Vascular Plants

Some of the most outstanding biological resources in the Monument are the diverse and unusual vascular plant populations found there. Although deserts in general have lower

plant diversity than more mesic areas, the area contained within the Monument has more species than would be predicted for this type of landscape. In addition, many of the plants found in this region are unique. The Canyonlands vegetation province, much of which is within the Monument boundaries, is considered the richest floristic region in the Intermountain West. It contains 50 percent of Utah's rare flora, with 90 percent of these rare and endemic species found on substrates typical of the Monument (Cronquist et al., 1972). In the United States, Utah has one of the highest rates of endemism (percentage of the flora considered for listing as threatened or endangered, and percentage of flora considered as rare species in the United States) (Davidson et al., 1996). Kane and Garfield Counties have the highest rates of endemism in the State. As a result, the Monument contains an astounding 125 species of plants that occur only in Utah or on the Colorado Plateau. Eleven species of plants found in the Monument are found nowhere else (Albee et al., 1988; Atwood et al., 1991; Shultz, 1993; Utah Natural Heritage Program, unpublished; Welsh, 1978). Consequently, this area has one of the highest rates of plant endemism in the United States (Cronquist et al., 1972).



High floral diversity and high rates of endemism occur for a variety of reasons. Four major floras are represented in the Monument. Plants from the Great Basin to the north and the Arizona deserts to the south dominate the flora, and are mixed with a smaller number of plants from the Mojave Desert to the west and the Great Plains to the east. With such a large pool of plant species to draw from, there is an unusually high number of species for a desert region.

Second, this area contains a large number of ancient plant species. Many areas of the Monument have been uplifted over geologic time with little deformation. Subsequent erosion has thus exposed large expanses of more or less "pure," unmixed substrates. In addition, this area was not directly affected by ice sheets in the Pleistocene and offered refuge to many plants during times of climatic and geological instability in other regions. As a result, this area contains many components of the past Arcto-Tertiary flora, which have both enriched the present flora as well as provided material for the evolution of new plant species.

Third, this area contains a rich concentration of diverse substrates occurring in close proximity to each other. Different substrates are a result of different environments present during deposition. Within the boundaries of the Monument are sediments that were laid down under a range of sea depths and under different oxygen concentrations. Fresh water and aeolian deposits are represented as well. Each resultant layer of rock, and soils derived from that rock, has different chemical and textural characteristics, and therefore supports different plant communities. Thus, a high diversity of substrates contributes directly to high diversity in plants.

In addition, the Monument contains lands that stretch from low deserts to high plateaus. These elevational gradients provide many varied environments and niches for plants to occupy, thus resulting in high numbers of plant species.

Speciation is generally favored by a combination of isolation and stressful environments.

Isolation occurs in this area on several scales. The entire Colorado Plateau is isolated by large mountains that act as barriers to the dispersal of plants adapted to arid and semiarid environments. On an intermediate scale, large expanses of substrates that differ in chemistry may act as a barrier to plants not adapted to those conditions. Many soils in the Monument have high levels of shrink/swell clays and/or salt levels that limit the successful establishment and growth of many plant species. Therefore, plants on these substrates tend to be highly specialized, and as a result, these soils can act as effective barriers to the dispersal of non-adapted plant species. On a still smaller scale, many small pockets of specialized environments occur throughout the Monument. These include habitats such as hanging gardens, dunal pockets, tinajas, highly saline soils, and year-round springs. Plants adapted to these conditions are isolated by large expanses of unsuitable habitat. Barriers can be fairly small, but highly effective. An example of this is the Waterpocket Fold. Even though this geologic feature is only 5 km wide in some places, it has acted as an effective barrier to many species of vascular plants. The subsequent isolation has resulted in differential plant speciation. As a consequence, the same formation of Mancos Shale supports a different flora on each side of the Fold.

Organisms have difficulty in adapting to extreme and/or unpredictable environments. Because of low precipitation and large temperature ranges, deserts are considered extreme environments. In addition, because areas with lower rainfall also experience high variability in timing and amounts, deserts are unpredictable environments as well. Certain soil types may exacerbate these extreme or unpredictable conditions. For example, while sandy soils provide plants with fairly constant, though low, levels of water and nutrients, clay or shale soils often experience wide fluctuations in the availability of these resources. Consequently, sandy soils generally support a wide variety of plant species with more generalist characteristics, while clay soils generally have a more restricted, specialized flora. Based on this, many of the fine-textured soils found in the



Monument are highly stressful, and have provided strong selective forces for plant evolution.

Much of this region has experienced geologic uplift with limited deformation. Combined with an erosional rather than a depositional environment, many substrates have been exposed with minimal mixing. Lack of mixing has resulted in large exposures of "pure" parent material, with little or no gradation between vastly different soil chemistries and textures. The resulting sharp contrasts between soils has resulted in isolation for many plant species, providing opportunity for speciation (Axelrod, 1960; Cronquist et al., 1972; Davidson et al., 1996; K. Harper, pers. comm.; Shultz, 1993; Stebbins, 1985).

Invertebrates

Few studies on invertebrates have been conducted in desert environments, and even fewer in remote regions such as those found in the Monument. However, given the number of unique and isolated environments in this area, many new and unusual species undoubtedly await discovery.

Many plant species have specialized pollinators. Since many plants in this region have highly restricted distributions, we can also expect to find associated invertebrate species with similarly restricted distributions. For example, a recent survey of ground-dwelling bees in the San Rafael Swell, Utah, a nearby area with similarly high rates of plant endemism, found an astonishing 316 species of these bees, with 42 of these species new to science (Davidson et al., 1996; T. Griswold, pers. comm.). Since the Monument contains a wider variety of substrates and a greater number of unique plant species than the Swell, invertebrate surveys would be expected to turn up a similar, if not greater, number of unique invertebrates.

Other uncommon or unique invertebrates are to be expected in the isolated and/or specialized environments found in the Monument. For instance, the limited dispersal capabilities of soil-dwelling organisms such as nematodes

and microarthropods may have resulted in the isolation necessary for speciation (Michener, 1979; Neff and Simpson, 1993).

Riparian Areas—Movement Corridors

Perennial streams are a highly limited resource in deserts. The Utah Division of Wildlife Resources estimates that over 80 percent of desert wildlife rely on these areas for food and/or cover, making them critical habitat for many animals (M. Moretti, pers. comm.). In addition, these areas also act as migration corridors for many species, including deer, neotropical migrants, mountain lions, and bears. The Monument contains several perennial streams that connect the high plateaus to the low desert, thus preserving these migration corridors and increasing the Monument's ability to conserve genetic and population diversity of plants and animals (IUCN, 1978; Kushlan, 1979; Meffe and Carroll, 1994; Newmark, 1985; Pickett and Thompson, 1978; Primack, 1993; Soule, 1987; Soule and Wilcox, 1980).

Adaptation to Disturbance

Plants and soil organisms are generally adapted to the disturbance regimes under which they evolved. Consequently, changing the type, quantity, or timing of disturbance can have profound, ecosystemwide effects. On the Colorado Plateau, where prehistoric soil disturbance was restricted to a few large mammals (J. Mead, pers. comm.), current populations of invertebrates and small mammals are limited compared to other deserts (Belnap, 1995; D. Davidson, pers. comm.), decomposition rates (and therefore nutrient availability) are very slow (Bowers et al., 1995), and the introduction of livestock and recreation has resulted in widespread changes in ecosystem functions.

The Monument offers many opportunities to explore the effects of such changes in land use. Within the boundaries are grasslands, blackbrush, and pinyon-juniper communities that have never been grazed by domestic livestock and that are seldom visited by people. In addition, there are waterfall-blocked canyons



that offer a rare opportunity to study relatively undisturbed riparian areas (Utah Wilderness Coalition, 1990).

Cryptobiotic Soils

Cryptobiotic soil crusts, consisting of soil cyanobacteria, lichens, and mosses, play an important ecological role in the Monument. Most soils in the Monument have varying degrees of cryptobiotic crust development. These crusts increase soil stability of otherwise easily eroded soils, increase water infiltration in a region that receives limited precipitation, and increase fertility in soils often limited in essential nutrients, such as nitrogen and carbon (Harper and Marble, 1988; Johansen, 1993; Metting, 1991; Belnap and Gardner, 1993; Belnap et al., 1994; Williams et al., 1995a, b).

Cyanobacteria and cyanolichen components of these soil crusts are also important contributors of fixed nitrogen (Mayland and McIntosh, 1966; Rychert and Skujins, 1974). These crusts appear to be the dominant source of nitrogen in cold-desert pinyon-juniper and grassland ecosystems in southern Utah (Evans and Ehleringer, 1993; Evans and Belnap, unpublished data). Biological soil crusts are also important sources of fixed carbon on sparsely vegetated areas common throughout the West (Beymer and Klopatek, 1991). Plants growing on crusted soil often show higher concentrations and/or greater total accumulation of various essential nutrients when compared to plants growing in adjacent, uncrusted soils (Belnap and Harper, 1995; Harper and Pendleton, 1993).

Cryptobiotic soil crusts are highly susceptible to soil surface disturbances such as trampling by hooves or feet, or driving of off-road vehicles, especially in soils with low aggregate stability such as the sands found throughout the Monument (Belnap and Gardner, 1993; Gillette et al., 1980; Webb and Wilshire, 1983). Cyanobacterial filaments, lichens, and mosses are brittle when dry, and crush easily when subjected to compressional or shear forces by activities such as trampling or vehicular traffic. Because crustal organisms are only

metabolically active when wet, reestablishment time is slow in arid systems. While cyanobacteria are mobile, and can often move up through disturbed sediments to reach needed light levels for photosynthesis, lichens and mosses are incapable of such movement and often die as a result of burial. On newly disturbed surfaces, mosses and lichens in desert environments generally have extremely slow colonization and growth rates. Assuming adjoining soils are stable and rainfall is average, recovery rates for lichen cover in southern Utah have been most recently estimated at a minimum of 45 years, while recovery of moss cover was estimated at 250 years (Belnap, 1993). Due to this slow recolonization of soil surfaces by the different crustal components, underlying soils are left vulnerable to both wind and water erosion for at least 20 years after disturbance (Belnap and Gillette, 1997). As soils take 5,000 to 10,000 years to form in arid areas such as the Monument (Webb, 1983), accelerated soil loss may be considered an irreversible loss. Loss of soil also means loss of site fertility through loss of organic matter, fine soil particles, nutrients, and microbial populations in soils (Harper and Marble, 1988; Schimel et al., 1985). Moving sediments further destabilize adjoining areas by burying adjacent crusts, leading to their death, or by providing material for "sandblasting" nearby surfaces, thus increasing wind erosion rates (Belnap, 1995; McKenna-Neumann et al., 1996).

Soil erosion in arid lands is a major threat worldwide. Beasley et al. (1984) estimated that in rangeland of the United States alone, 3.6 million ha has some degree of accelerated wind erosion. Relatively undisturbed biological soil crusts can contribute a great deal of stability to otherwise highly erodible soils. Unlike vascular plant cover, crustal cover is not reduced in drought, and unlike rain crusts, these organic crusts are present year-round. Consequently, they offer stability over time and in adverse conditions that is often lacking in other soil surface protectors. Unfortunately, disturbed crusts now cover vast areas in the western United States as a result of ever-increasing recreational and commercial uses of these semiarid and arid areas. Based on the



results of several studies (McKenna et al., 1996; Williams et al., 1996; Belnap and Gillette, 1997) the tremendous land area currently being impacted may lead to significant increases in regional and global wind erosion rates.

Within the Monument, grazing, off-road vehicles, and other forms of recreation have greatly impacted crustal integrity. As a result, it can be expected that soil erosion and nitrogen inputs in these areas have been greatly reduced. On the other hand, the Monument contains many areas that have not received extensive grazing, where crusts and other soil processes are relatively undisturbed.

Lack of Well-Traveled Roads

Many animal species are affected by habitat fragmentation. Fragmentation can be a result of radical land use changes such as the construction of houses, or of more subtle developments such as roads or trails. Depending on the species of concern, severe disruption of migration movements, foraging patterns, and/or reproductive success can result from fragmentation. The Monument is an important resource in that large, roadless areas occur within its boundaries. Of equal importance is that, of the roads that do exist, most are seldom traveled, thus reducing their fragmentation impact (Bolger et al., 1991; Davidson et al., 1996; Harris, 1984; Oxley et al., 1974; Rost and Bailey, 1979; Saunders et al., 1991).

Roads also pose problems because they act as corridors for exotic plant and animal invasions. Because roadsides are disturbed habitats, they generally favor those species evolved to succeed in such environments. Car tires, clothing, and pets can rapidly spread exotic plant propagules over large areas. Animals often hitchhike in cars. For these reasons, both low numbers of roads and limited traffic on existing roads are essential to keeping exotics to a minimum.

Over 50 percent of the western United States is currently dominated by exotic plant species, threatening the population viability of many

native plants and animals. Over 300,000 acres are irreplaceably converted to exotic annual grasses a year, increasing fire frequency that results in loss of forage and habitat for both wildlife and livestock. Once an ecosystem is dominated by exotic plant species, it is generally difficult or impossible to reestablish native species (Bergelson et al., 1993; Billings, 1990, 1994; EPA-EMAP, unpublished).

What Scientific Opportunities Does the Monument Offer?

The previous description of the biological resources found within the Monument gives a picture of the extraordinary scientific value of the Monument. The Monument provides an unparalleled opportunity to study speciation and evolution, independent of climate, given the close juxtaposition of diverse substrates within the Monument. Having ancient plant species alongside new species gives us the opportunity to examine how plant species adapt to different conditions. The presence of steep elevational gradients gives scientists the opportunity of sort out the differential roles of temperature and precipitation in the structuring of plant and animal communities. The juxtaposition of elevational gradients with substrates of diverse depositional origins gives scientists an opportunity to determine the respective roles of soil chemistry, soil physical characteristics, rainfall, and temperature in factors controlling community structure and functioning. And of great importance, these substrates and elevational gradients are replicated within the Monument, giving scientists the ability to speak much more confidently of their findings, as well as to extrapolate their results to a much larger area.

Relatively undisturbed habitats can provide information on the natural variation of ecosystems, thus providing a baseline against which to measure the effects of different land uses on the major vegetative communities.



Undisturbed habitats also provide goals for restoration and management. Replicated perennial streams offer the ability to study animal migrations and the importance of riparian areas to desert species. Given limited temporal and spatial disturbance on the Colorado Plateau, ecologists can use this area for comparison with other deserts and ecosystems that have evolved with much larger and more frequent disturbance so that we can better understand the influence of disturbance in structuring communities.

Whether insights gained from areas of one size can be applied to areas of a different size is an important ecological question. Given that the Monument contains many different, discrete, and relatively simple ecosystems that occur on several scales, this area is ideally suited to answering such questions. Effects of isolation on different scales and in different habitats can also be answered here, using communities such as hanging gardens, salty soils, tinajas, shallow soils, and dunal pockets.

The Monument is also well-suited to answering questions about global climate change. Because it is dry, and located on the boundary between ecosystems dependent on summer precipitation and those dependent on winter precipitation, vegetative communities in this area should be especially sensitive to changes in precipitation timing and amounts. The presence of elevational gradients makes this area even more interesting for such studies. Packrat middens in the area give us the opportunity to reconstruct past floras, and therefore past climates. This, in turn, aids us in understanding the effects climate change has had on plants and animals in the past, better enabling us to predict what might happen with future climate change.

Relatively few systems have as low spatial and temporal disturbance as in the Monument. And even fewer systems, especially in the western United States, have areas ungrazed by livestock. As a result, the Monument offers a unique opportunity to study the effects of disturbance on a landscape not evolutionarily

adapted to such disturbance and how such disturbance structures plant and animal communities.

Is the Monument the Minimum Size Necessary to Protect the Listed Objects of Interest?

Yes! Several characteristics make an area especially valuable for science. One of the most important is the ability to replicate studies across a large area. Replication gives scientists the opportunity to make much stronger statements about the results of their studies. Validating results found in one area using additional areas enables scientists to justify extrapolating their results to much larger areas. By containing replicates of the different major substrates, vegetation communities, elevations, and perennial streams, the Monument is of far more value to science than areas with only one or two examples of each.

There is another important reason for replication. As pressures increase on natural resources and some are inadvertently lost, having multiple examples of different resources will become increasingly important to ensure their preservation. For example, multiple corridors for animal movement between high plateau and low desert regions provide replication for scientists as well as assurance that some migration corridors will be protected, in spite of wildfire, development, or other unforeseen events that may compromise other corridors.

It is well accepted in conservation biology that the connection of protected areas increases the value of those protected areas. Consequently, the connection the Monument provides between Glen Canyon, Canyonlands, Grand Canyon, Capitol Reef, and Bryce National Park units increases the value of all these areas for protection of viability of plant and animal populations.



Sheer size and vastness of the Monument are essential to protect the objects listed in the proclamation. Great diversity of habitats is critical to protection of natural resources, especially wildlife. Protection of the "plant speciation laboratory" that the Monument provides is dependent on large expanses of substrates as well (IUCN, 1978; Kushlan, 1979; Loope et al., 1988; Meffe and Carroll, 1994; Newmark, 1985; Pickett and Thompson, 1978; Primack, 1993; Soule, 1987; Soule and Wilcox, 1980).

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Perspectives on Science in the Monument

Hellmut H. Doelling

... Thank you very much. You are a wonderful group of scientists and managers and I hope you enjoyed our field trip of the last 3 days. I certainly did and I learned a lot on the trip. I began to understand that we are all brothers and sisters in science; that the sciences are all related. Geology, soil science, and botany are important to archaeology, and in turn, archaeological studies help interpret the geologic history. Some kinds of plants grow well over particular rock types and the local plant growth helps geologists map rock formations. There are many other examples of disciplinary overlap and interdependence, but they are too numerous to describe here.

I was asked to speak about data gaps and the "big picture" with respect to science and the new Monument, and how to make the Monument a science-friendly place. I assume I was asked to be on this panel because I have walked over most of the Monument area during the course of my career. I first became acquainted with the area in 1961 when I was hired to give advice to coal drillers working at the south end of the Kaiparowits Plateau. Later, as a part of my job with the Utah Geological Survey, I walked over the entire coal-bearing part of the Kaiparowits Plateau. Coalbeds, as many of you know, are exposed on canyon walls. After walking out most of them, I have been accused of having one leg shorter than the other.

A significant part of my career was spent working in the area that was to become the Monument. I geologically mapped all of Garfield and Kane Counties and so covered the Monument area. As I did so, I fell in love with the place. Even though most of my work was done for economic purposes, I always had

it in mind that if mining were to take place, it would have to be done in a careful way. Mining operations should be prevented from ruining the beauty of the landscape. I get angry when I see all-terrain vehicles (ATVs) being driven over soft formations in the Monument. ATV tracks on a soft geologic unit leave imprints or ruts, which the next torrential rain will erode into an ugly scar that will last a lifetime. An ATV can do more erosional damage in a day than a cow could walking over the landscape if its lifespan were 100 years.

Let me return to geology. Geology is a research-oriented science and an information-gathering science. It you look in the dictionary, it says that research is careful inquiry or experimentation aimed at the discovery and interpretation of facts and in finding practical applications for those facts. Geology is the study of the earth's crust, the study of rocks.

In essence, geologists try to answer five questions about rocks: 1) "What are they?" 2) "Where are they?" 3) "What shape are they in?" 4) "How did they get that way?" and 5) "What can they do for me and you?" The last question has been the driving force for practically all previous geologic research done in the Grand Staircase-Escalante National Monument (GSENM). The better geologic publications covering the GSENM area were produced because of economic incentives. Question No. 5 must remain the driving force for geologists if geologic research is to survive, because everything that man studies is for his benefit. Justification for research must involve goals that will maintain or improve our standard of living or that will provide basic human needs. In this light, I think the Monument presents a great challenge to geologists.

Most earlier studies in the Monument area were initiated by the Federal government,



Utah State government, and private enterprise. Their goals were to find material resources, energy resources, construction materials, fertilizers to grow food, and to find additional water resources. They also studied the geologic hazards present in the Monument area in order to make local life and living safer. They found the aesthetic geologic resources that are so plentiful in the Monument. Geologic research also finds and explains things to pique the curiosity of man—geologists love to find the biggest, the smallest, the most bizarre, and the most unusual or unique geologic features.

With the establishment of the Monument, the incentives for answering the first four questions seem diminished and the fifth is in jeopardy. Should geologic research be diminished? Some have said that geologists should look for recreational resources, but this is not in the realm of geology. People can play in a schoolyard in the Bronx. I was born in New York City and there was plenty of recreational activity there. We can ride bicycles in the parks of Los Angeles and I can swim in a backyard pool. I can take a drive down a freeway and relax in the sun on a beach in Delaware (which by the way is smaller than the Monument). You can observe hummingbirds on the Great Plains and see wildlife in a zoo. However, if we had our "druthers" most of us would prefer doing those things where the geology is gorgeous, colorful, big, small, unique, bizarre, or whatever. So in spite of its basic goals, geologic research must have a place in the Monument. The area was chosen to be a Monument because of the geology, and without it there would be no Monument. The geology affects the other natural sciences in the Monument and I feel that the botany, zoology, and archaeology are really fingers inseparately connected with the geology.

The first two questions, "What are they?" and "Where are they?" are really inventory or cataloging questions. Completing the geologic inventory is done by geologically mapping the area. It is the beginning of all geologic research and is the most important geologic activity. If you don't have a good geologic map, everything

else that you base on that map will be wrong. Geologists can't begin to explain how it got that way or if something is there that is good for me and you until mappers prove its existence. In my work I am often asked, "Hasn't all this been done before?" Then I receive that look that tells me they think I'm working on another Government "boondoggle." Politicians commonly have the same view. They continually ask, "When will your project end?" They have already decided to spend their money on something else, usually something to "put out a fire." Many do not understand that research is a never-ending activity and is the way that humanity really progresses. Surely there are many intermediate goals to finish, but from them spring many more.

You may remember that in ancient mythology there was a monster, that if you chopped its head off, two more would spring up in its place. That is the way research is. You answer one question and two more spring up in its place. Research is never-ending. For example, in medical research, Andreas Vesalius published a complete anatomy of the human body in 1543. One might ask why we still spend money on medical research. The inventory of the human body remains incomplete and may never become complete. I was a student of Dr. W.L. Stokes at the University of Utah, and as a part of my dissertation had to present him with a list of 10 research products that remained that I had not answered. I gave him a list of 50, and I think there are thousands of unanswered research studies left to do in the Monument. Don't you agree?

The GSENM covers an area about 10 times that of my dissertation area and most past geological research was justified in hopes of finding economic resources. I know that "mining" is a dirty word to some, especially in National Parks and Monuments. However, thanks is due to the instigators of those studies, because our present understanding of the noneconomic aspects of the geology has been gleaned from their reports. Government-financed publications caught the eye of resource-oriented corporations, who then spent millions in drilling and trying to find out what was there. We are the



benefactors of what they learned. They, however, did not finish the job and left at least two unanswered questions for every one they answered.

We still don't know the source of the uranium found in the Circle Cliffs. We still don't know where the metals (lead, zinc, copper, cobalt, and silver) associated with the uranium came from and how they were emplaced. Silver is known to be present in the Co-op Creek Limestone Member of the Carmel Formation in greater than normal amounts. Why is that so and what is the source? Why is the petroleum at the Upper Valley oil field found on the side rather than on the crest of the anticline? Normally oil migrates into the crestal area of an anticline. Is this condition present at all the other anticlines in the Monument? Like the Upper Valley anticline, good shows are present at the crest of most of them, but none have been tested on the flanks.

I remember when similar questions were proposed about the petroleum possibilities of the Uintah Basin. Many thought that significant amounts of petroleum would never be discovered there. Hadn't all the prudent thinking of the past been followed and tried out? If we always follow the old ideas, nothing new will ever be found, learned, or gained. I have a whole list of unanswered geologic questions about the Monument area. You have all heard questions such as, "How are Moqui balls formed?" "Why is that formation brown and that one green?" For many of such questions I have had to say, "I don't know." As you can see, we have lots more to learn and not all studies are for the economic reasons, or are they?

I have a good research project for all of us to work on. How can we extract all the Btus locked up in the coal under the Kaiparowits Plateau without upsetting the environment? It shouldn't be any tougher than getting to the moon. Geology is not just a scenery enhancer, and as one rancher put it, "You can't eat scenery."

As we talk about science in the Monument, I would like to suggest to managers to make an effort to understand the scientific principles operative in the Park. Managers should understand them almost as well as the "outside" professionals. In most Parks and Monuments in which I have worked, I have found few managers and rangers that truly understand geologic principles. Although most work in Parks and Monuments founded on geology, there are hardly any with geology degrees. If managers are to do their job properly, they need to understand the geology. Rangers and managers should be involved in some research of their own to keep in touch. Once "stuck" behind a desk, real research ceases and managers will lose their love of the land. How can a Monument be properly managed if the managers don't understand what they are managing?

Don't curtail outside research. Make every effort to make it easy to do. No one should be hindered from doing legitimate research. The BLM originated as an organization based on multiple use and this is a good beginning. All kinds and facets of science should be helped and supported, especially interdisciplinary research. University professors, students, private individuals, and even industry professionals have good ideas that we need. I sometimes think about a "crackpot" named Alfred Wegener (probably one of my relatives), who thought the east coast of South America fit very nicely against the west coast of Africa. As a university student I remember a professor saying: "This is a course in advanced structural geology and we have to cover all the theories no matter how silly they are. I want to tell you about a silly theory called continental drift." Continental drift has since been widely accepted and is thought by many to be fact. When considering research, avoid being totally loyal to "turf" people who say their ideas are the only correct ones. The other fellow may have an idea that is just as important. We must consider this when research projects are evaluated and look at each openly; I believe that it is extremely important to do so.



With respect to geology I recommend the following:

1. Complete all of the 1:24,000-scale quadrangles that have not been geologically mapped. Larger scale maps should be prepared for more important areas, especially for areas that are expected to receive the greatest use. Map at the 1:12,000 or 1:6,000 scales when necessary.
2. Educate the public on the importance of geology (and the other sciences) to their welfare. There is opportunity in the Monument to show the public where minerals and energy come from and about potential geologic hazards. Tell the public what a landslide is, its danger, and how a landslide develops. Teach the public what causes earthquakes and how their effects are minimized. Teach the public why it takes years to create nature's handiwork and why it takes a day or two for man to destroy it (and why it is important not to destroy it). Find a way to truly educate the public rather than appealing to emotions. The Monument is a perfect laboratory in which to do this.
3. Study the potential geologic hazards of the Monument and find ways of overcoming or mitigating the danger. Allow the public to observe these activities in the field and get them involved. The biggest problem is unwanted erosion.
4. Teach the public not to "waste" the geologic environment. In the past, tourists have been far more effective in degrading the environment than all previous mining and drilling operations put together. Most old mining ventures in the Monument were left reasonably clean after shutdown (I know, I was there). Artifact-and-souvenir-seeking tourists literally "wasted" these sites afterwards, breaking into buildings, smashing windows, tearing out boards and burning

them, and so forth. I like to drink pop and eat candy bars as much as anyone out in the desert, but I carry the trash out.

Tourists, ranchers, deer hunters, and even some scientists leave beer bottles, pop cans, diapers and tissue, candy bar wrappers, gum wrappers, cigarette and cigar butts, and all kinds of cardboard containers along every road and every path. I have worked in the Moab area during the time it was discovered by the tourists and have seen what has happened, and I have to cry. I hope that everyone that cares will make a great effort to educate the public, that this Monument is one to save for future generations. We need to conserve, preserve, and do whatever is the right thing in the Monument area.

That is all I have to say. I am nearly through "ranting and raving" about one of my favorite areas. One more thing. We need to preserve the old mines in the Monument as well as the scenery. The Utah Geologic Survey, for whom I work, has a sister agency that seals old mines because people walk in them and hurt themselves. We should train the public to respect old mines and not enter them without proper equipment. They should be preserved. They are a part of our historical heritage and are most interesting. When you see a mine dump, you can see the hard work done by the early miners, how mining helped develop the remote areas of the West, and see how important mining was to the early history of this area. The public needs to know that mining is still necessary. Some miners may have been disrespectful to the environment. Perhaps they didn't have the proper guidance or the proper rules. Perhaps Federal laws in place during earlier times aggravated damage to the environment. Nevertheless, the public should know that we mined a little bit of uranium from the Circle Cliffs area, that 25,000 tons of coal were removed from the Kaiparowits Plateau to keep the school children warm, and that there are 30 billion tons left.

Thank you.



Designation of the Grand Staircase-Escalante National Monument: The Role of Science¹

Thomas C. Edwards, Jr.

I want to thank Terry Sharik from Utah State University, and others involved in this conference, for inviting us here today. And I say "us" because present here are other individuals that were, and are, also involved in this process. My role was simple, being called back to Washington, DC with Jayne Belnap for consultations on the Monument designation and boundary delineation. And I want to point out that as far as "certainly" in science is concerned, somebody has a wicked sense of humor, because August in Washington, DC, is "certainly" not my idea of a place to go to.

What I'd like to focus on today are some of the issues we faced when we sat down to discuss the Monument designation, what I refer to today as being caught between the Scylla of Science and the Charybdis² of Reality.

As scientists, we love to pontificate. I have this wonderful inverse relationship between the amount of hot air people sometimes expend on an issue and its relative importance. And often scientists do that, espousing theoretical constructs—our Scylla of Science—until we confront this Charybdis of Reality. In this particular case, our Charybdis was information: what was out there and how good it was, so that a decision could be reached about the Monument boundary. And although Secretary of the Interior Babbitt spoke rather eloquently about integrating "everything" when making this kind of decision, it still boils down to

drawing little lines on a map somewhere. You have to get the crayon, sit down, and draw boundaries. And as much as the scientist in me would love to draw those boundaries based solely on science, the Scylla of Science I live by often gets sucked into this whirlpool, this Charybdis of Reality.

I first want to talk about some of the thought processes that at least I underwent when we were thinking about the Monument designation. And second, how would you meet with this criterion of scientific curiosity that is implicit—actually explicit—in the designation of a Monument? Simply put, I was asked the question by Ron Pullium, the then-Director of the now-defunct National Biological Service, what would you do if you had a very large-scale, outdoor scientific laboratory?

Like most scientists, we march boldly on in. It's generally accepted that the conservation of biological diversity, within a given area, is best achieved by maintaining the ecological integrity of the wildlands that such a boundary might encompass. One of the basic principles of this idea is that first you try to represent all of the native ecosystem types in a given area. You certainly want to try to maintain viable populations of the plant and animal communities that it contains, while also maintaining the ecological and evolutionary processes in that particular area. From a management perspective, you have to be responsive to both short- and long-term change, because management of these areas is a lot different from simply allowing natural processes to occur.

¹ Modified somewhat by the presenter from a tape-recorded version to minimize the embarrassment he felt when he discovered just how long-winded he was!

² From Greek mythology, sometimes interpreted as two equally hazardous alternatives.



So these were some of the basic thoughts I had in the back of my mind when we walked in, or at least when I walked in. And right away we encountered some unexpected hazards. Scientists often assume that our science and political and economic perspectives are going to clash, and that these conflicts can occur intentionally. But one of the things that became apparent (and I think Governor Leavitt brought this point out quite nicely) was the unexpected hazard of miscommunication even amongst ourselves.

Some questions we encountered—not from the political and economic perspectives we often assume are opposite of us, but from those we assumed were knowledgeable since they were proposing the Monument—included: “Why isn’t a creek a boundary, they make wonderful little dark lines on maps!” “Why isn’t one of everything enough—can’t we maintain the ecological integrity of systems with just one?” And, “Why so big, why do these things have to be so big?” And again, much like creeks, “Why isn’t a road a corridor?”

In general, the principles I put forth earlier represent, I guess, some of the central tenants of conservation biology. These are cheap. Anybody can sit down over tables and talk about these ideas, but to collect the information that is actually necessary to implement these principles is terribly, terribly expensive, as I’m sure the planning team would agree with me on. Utah, relative to many places, has an abundant wealth of natural history studies. Just the uniqueness of this State alone has driven a lot to scientific curiosity. Lots of published and unpublished information is available. We have a recently derived cover map for the State, which is a great way to look at big-scale issues, and, at least from my perspective as an animal ecologist, lots of predicted distributions for some terrestrial vertebrates.

Yet even when you bring that kind of information to the table, it’s amazing how we, as scientists, become our worst enemies. The information is too coarse or too fine. My favorite excuse is, “I don’t know everything about all the species, so I don’t want to make

a decision.” I love that one. The effect of uncertainty in ecological information requires a risk assessment perspective in the decision-making process, particularly since a lot of ecological information is models. If you start dealing at big spatial scales, which is what this Monument is about, you will be modeling. There is just no way we can trek over every square centimeter of that kind of ground and inventory and catalog everything.

But even with these road blocks, eventually the Charybdis of Reality is confronted, because somebody will make a decision. Somebody is going to say, “Sit down and draw the lines”—because if you don’t draw them somebody else will. The little dark lines that are typically found on maps and the principles of conservation rarely, if ever, coincide. Most of the Monuments, most of the National Parks, as most of you are well aware, have been set up for cultural and aesthetic reasons. They haven’t been based on principles for maintaining the integrity of ecological systems. Now we, as conservationists, take advantage of these lines and these Monuments and National Parks, these reserved lands, to actually allow us to do that, but that’s not how they were set up. To maintain ecological integrity, the little dark lines must, in part, maintain linkages and corridors between separated areas. They must allow for some replication and redundancy in the coverage of ecological systems, and be ecologically rather than politically based. They must buffer outside influences and provide sufficient space for ecological processes to continue.

In terms of linkages and corridors, the existing Parks and Wilderness Areas in Utah afforded a unique opportunity to think about a core reserve area, one of the major principles of reserve design, that stretched from the upper reaches of the Aquarius Plateau to similar areas that are on the other side of the Arizona border. In Figure 1, existing Parks and wildlands are dark, with white being, of course, the Monument boundary. One of the things we considered was stretching these boundaries over to Zion and Cedar Breaks, in part because there’s sufficient scientific evidence that

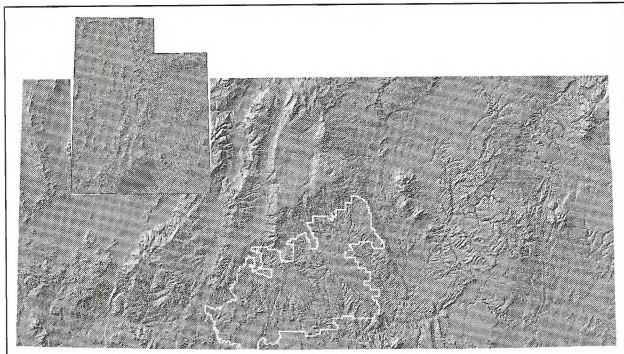


Figure 1. Grand Staircase-Escalante National Monument boundary.

indicates isolated pockets often lose components of their diversity through time—certainly the large, wide-ranging animal components. So we did think of alternative definitions or delineations that would allow some linkages between these different areas.

Figure 2 refers to the two R's of redundancy and replication. The terms are synonymous, yet when I think of redundancy from an ecological perspective, I think of the same kind of redundancy in airplanes. If one system goes down there's a backup that covers you. So redundancy is a means of protection against large-scale ecological catastrophe. When, for example, Hurricane Hugo hit the Francis Marion National Forest in the Carolinas, it wiped out an important core area of habitat for red-cockaded woodpeckers. If that had been the only core area for the species, then there would be serious problems with respect to that bird. Replication, shown in white and thin dark lines inside the boundary delineation, provides us, the scientists, opportunities for defensible scientific inquiry of whatever kinds of ecological impacts that we wish to examine. The white lines represent the NRCS big order watersheds, and with respect to the Monument, we have a lot of replication of watersheds. And

the same thing is apparent if you examine the thin dark lines, which are first- and second-order streams. Once again, though, ecological vs. political boundaries clashed. Some of the initial boundaries we looked at were drawn down the middle of some of the waterways—the Paria and the Johnson. And I mean right down the middle, which of course effectively slices a watershed in half. What happens on the west bank river affects the entire watershed, even if the east bank itself is protected. I'm pleased to say that many of the boundaries were shifted eventually to encompass full watersheds rather than slicing them down the middle.

I need to address the importance of buffers. If you were to consider the Monument a core reserve area, you have an area that's surrounded by multiple use buffer zones, which can support a wider range of human management activities. These buffer zones serve to minimize edge effects, enlarge the effective core reserve area, and ensure the metapopulation persistence of plants and animals inside the core area. Buffering is important. In Figure 3, the dark squares are, of course, Utah's State Trust Lands, which are embedded in this matrix of surrounding multiple use lands and the

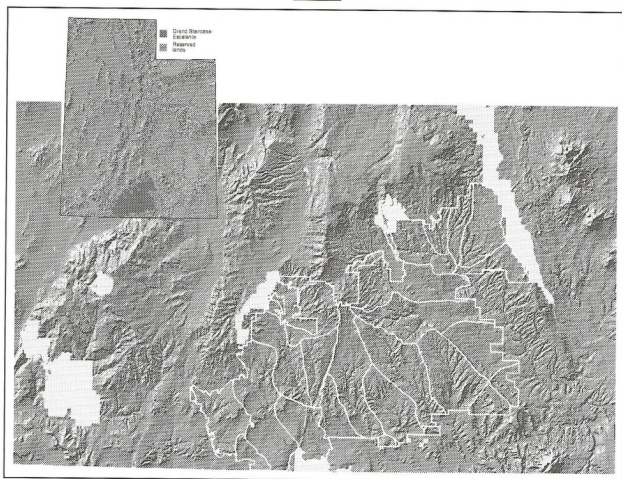


Figure 2. Replication in the Monument area.

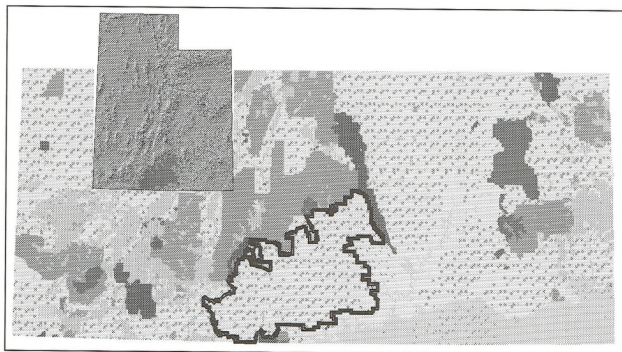


Figure 3. Buffer zones surrounding the Monument.



Monument itself. Dealing with a management issue like this is exceedingly difficult, and I certainly don't envy the management team for having to deal with this issue. It's a very difficult problem.

The question of why bigger is better is really a question of scale. Large areas are good for protection. It's really a function of sampling. You throw out a big net and you're going to capture more things than if you throw out a little one. And the Grand Staircase-Escalante is a very big net, capturing diverse components of biological diversity. Hence it is probably better poised to maintain the ecological processes as well as provide management options. And certainly with the surrounding reserved lands we already have (those ranging all the way from the Aquarius Plateau to the North Rim of the Grand Canyon), it's now part of one of the largest contiguous parcels of reserved public lands in the United States. It's very big-scale, and we are fortunate it is here. So what do we do with it? What do we do with a rather large-scale scientific laboratory?

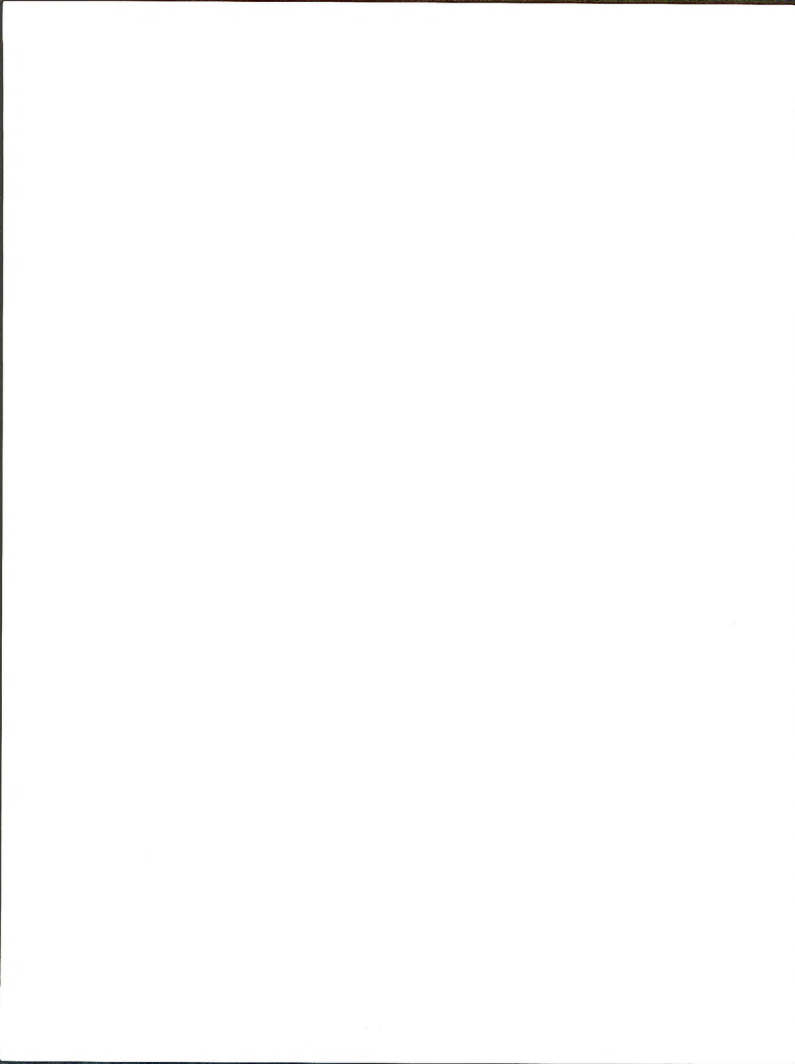
And now I admit to personal biases. I'm basically a large-scale ecologist. I like to look at large-scale issues. And it is a large-scale Monument. It was set up that way, designed that way, and I would argue that the major area of emphasis ought to be on large-scale issues. For example, we need to examine the usefulness of coarse-grained ecological models and fine-grained analyses for inventorying and managing biological diversity. And how can we integrate coarse- and fine-grained scales, because we will never, never, never have the sufficient funds to go out and do the kinds of sampling intensity that we, as scientists, all recognize we need in order to get a picture of what's actually happening on the landscape.

We will be forced into large-scale modeling efforts, whether we like it or not. So somehow we have to link our fine-scale research with large scale models.

We have, for example, an absolutely wonderful opportunity to use the Monument to look at the importance of corridors and linkages for dispersal and movement patterns. It's one of the central themes we used when we delineated these boundaries. It drives many of the principles of conservation biology. It can help answer some questions of metapopulation stability: "Are these big areas really better?" "Can they actually maintain populations more effectively?" "What can we do in terms of the multiple use management activities on these systems?" I think we've got some opportunity to look at some hairy management questions: the impacts of point-oriented resource extraction on the integrity of surrounding ecosystems, the role of roads as vectors for nonnative plant and animal species. We can look at mechanisms for restoration of degraded ecological systems. We have replication of some of these systems inside the Monument, so let's try some new and innovative management methods. Let's apply some of our scientific knowledge inside this large-scale Monument to examine these crucial management issues. And one of the biggest future impacts we face as managers is recreation, and its impacts on the integrity of ecological systems. And we now have a chance to study recreation impacts.

So in conclusion, I'd argue then that with respect to this new Monument, its large scale, we should expend much of our energy and emphasis, as scientists, on exploring large-scale issues.

Thank you.





Integrating Science Into Natural Resource Planning and Management

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The importance of integrating science into natural resource planning and management has increased as our wildlands have diminished and conservation issues have become increasingly politicized. It is more important than ever that difficult and potentially contentious decisions be based on the strongest possible science. I am a particularly strong advocate of the need for quality science as a basis for land management decisions. But I am also a strong proponent of the importance of protected areas for science—there is much we can learn from our wildlands and how we interact with them. Both of these needs must be addressed in the planning and management of the GSENM.

The opportunity (and challenge) faced in building a framework, or partnership, for integrating science into the planning and management of the Grand Staircase-Escalante National Monument is truly exciting. It is an opportunity to set a precedent that will form a model for future Federal land management. As Secretary Babbitt indicated this morning, this meeting is a milestone; it presents an opportunity to look at science as an integrated whole—across agency lands and at a large spatial scale. I am particularly interested in how you build partnerships to accomplish this, how you assure that the best quality and most

appropriate science is available, and how you assure that the science that is available is understood and used. In short, how do you effectively encourage and facilitate quality science and its application to management? I've seen big dollars spent on studies that weren't very useful. I've seen top scientists avoid working in protected areas, such as parks and wilderness, due to concerns that such areas limit manipulative research or that management will change, and with it, policies regarding what is appropriate or acceptable. I've also seen good, relevant research sit on the shelf unused. Such problems most often result from a lack of understanding and/or a lack of communication. It is for these reasons that I fully endorse the approach of this symposium and the followup workshop with the GSENM Planning Team. The bringing together of scientists and managers at the initial planning stages, as a first step in building a partnership, is the way to do it!

Before continuing, I think it would be useful to reflect on my background, my qualifications for standing here before you. The first 21 years of my professional career, I served as a research scientist with the National Park Service, and briefly with the fledgling National Biological Survey, at Sequoia and Kings Canyon National Parks in California. During that time, I directed development of interdisciplinary research programs to address issues related to fire ecology, visitor use impacts, acidic deposition, and global climatic change. During those years, I became increasingly concerned that much of the science available to or produced by the Federal agencies was not effectively incorporated into management plans and programs. Too often managers didn't understand what science could do for them, and scientists didn't



understand the larger management or policy context of their work. I found I was increasingly focusing my time on overcoming these obstacles by facilitating communication between scientists and managers. I would seek out those interested in such collaboration. In 1994, the U.S. Forest Service offered me an opportunity to become director of a new national, interagency, interdisciplinary, research program designed to develop and apply the knowledge needed to improve management of wilderness and other natural areas. I believe the Aldo Leopold Wilderness Research Institute, located on the campus of the University of Montana in Missoula, represents the type of cooperative endeavors needed by the Federal land management agencies. Supported by an interagency agreement among the Forest Service, Bureau of Land Management, National Park Service, Fish and Wildlife Service, and the Biological Resources Division of the U.S. Geological Survey, and including various cooperative arrangements with university and private sector scientists, the Leopold Institute strives to leverage the limited funds and expertise of these agencies in addressing social and natural science issues important to the understanding and management of wilderness and other protected areas. There is much that can be learned by the GSENM from our experiences at the Leopold Institute.

Perhaps the most important lesson I have learned from my experiences to date is that there are no proven models for how to effectively integrate science into natural resource planning and management—whether at the local, regional, or national levels. Agencies, individual scientists, professional societies, and even Congress continually struggle with how to assure the best quality science is available to and used by land managers. Planning processes such as Limits of Acceptable Change (LAC) and Visitor Experience and Resource Protection (VERP), and agency initiatives such as ecosystem management, have been attempts to accomplish such (Christensen et al., 1996; McCool and Cole, 1997). Various reports by the National Academy of Science and other

groups (National Research Council, 1992) have recommended possible solutions. Federal laws, such as NEPA and NFMA have attempted to mandate science-based management. The dilemma continues today, as reflected in the Department of the Interior experiment of moving the research function of the Interior agencies to first the National Biological Service, and more recently the U.S. Geological Survey. If there is any lesson to be learned from these experiences, I believe it is that the right individuals and effective communication are more important than even the best policies, laws, or organizational structures.

Yet, there can be no question but that in today's natural resources environment, where special interest groups, public involvement, and court battles require well-supported decisions, it is more important than ever that management proposals be supported by sound science. We are long past the day when agencies can rely on intuition and in-house expertise to make decisions. Solid, defensible, information is critical.

So, how do you assure the best possible scientific input is available for planning and management? Unfortunately, it is not always as easy as hiring a new staff member or turning to your local university scientist or even supporting a research branch in your agency. Information by itself is not enough; it must be the right kind of information and you must have people who know what it means and how to use it. Agencies can do a lot to facilitate or provide logistical support for science, but effective utilization of science requires more than that. It requires communication. And effective communication requires skill, commitment, time, and effort. It must include both managers and scientists in early discussions of what the issues and needs are, and how that information will be used. The chances of success are maximized if all parties have understanding and ownership. If scientists understand the context of why the information is needed and how it will be used, and managers understand the timing and other limitations of the data to be provided, there is



a much improved chance that it will be effectively utilized. Communication, early and often, is a key to success.

A lesson that has often been hard for managers to learn is that it is generally inappropriate to expect (or ask) science (or scientists) to make recommendations, much less decisions. The proper role for science is to provide information, to provide an understanding of how things work as well as unbiased assessments of the consequences of alternative actions. It is the role of managers to make decisions using science as one of many inputs. It is important to remember that decisions, though often science-based, are largely value judgements. When scientists get involved in value judgements, it may be at the cost of compromising their scientific integrity, and ultimately their credibility. In addition, it is unlikely that a scientist, who is generally trained in one or more relatively narrow disciplines, will understand all of the implications (ecological, social, and political) of any given decision.

It is also important to recognize that most science requires time. Newly undertaken research or monitoring studies are likely to be of limited value in addressing today's crises. Yet, without a solid research basis, we won't have the answers we need to address tomorrow's questions either. To assure the long-term protection and sustainability of wildland ecosystems, it is critical that the Federal land management agencies develop the scientific support that will assure that the understanding exists to address tomorrow's questions when that understanding is needed.

In the natural resources world we live in today, we increasingly find the solutions to difficult questions lie in the integration of the social and natural sciences. This symposium, in focusing on the physical and biological sciences, suffers from a lack of social science input. Information on social consequences and preferences is critical to sound land management decisions. Human impacts, perceptions, and reactions repeatedly play major roles in determining the outcomes of most natural resources debates. They will likewise be major

determinants of future options and choices in the planning and management of the Grand Staircase-Escalante National Monument and must not be ignored. The Monument needs to find a way to effectively incorporate the social sciences into its planning and management.

Since none of the parties involved in the GSENM, or the Great Basin in general, have adequate resources or expertise by themselves to address the scientific needs of the planning and management process, we must also recognize the importance of cooperation. Pooling resources and expertise—among the Federal agencies, state governments, universities, and nongovernmental organizations—will be critical to solving many of the questions that must be addressed. I encourage the Monument staff to take a leadership role in facilitating such collaboration. We will all benefit from sharing expertise and resources.

Finally, I want to emphasize that it is not just that management of the GSENM can benefit from science, but that the Monument, like so many other natural areas, has tremendous value for science. It is important to recognize these values and find ways to effectively encourage and facilitate scientific study that may be of greater value to the region, nation, or society in general (including for the sake of science itself) than to the Monument itself. Understanding of basic ecosystem processes, or the interaction between climate and hydrology or plant succession, for example, may be of limited immediate value to the management of the Monument, but of potentially great value to the long-term sustainability of arid ecosystems. The concept of a dual role of "Science for the Monument" and "the Monument for Science" is consistent with the National Research Council (1992) report on science in the National Parks.

The support of quality science—whether for the Monument or for science itself—can be greatly facilitated by providing a management and logistical infrastructure that encourages scientists to work at the GSENM. This might include dedicated staff to coordinate activities, a reference library, laboratory facilities, and a



central repository for information. Mechanisms for facilitating communication between Monument staff and scientists working in the region should also be developed. These might include newsletters, workshops, and periodic symposia.

In conclusion, I draw your attention to a recent U.S. Forest Service (1997) publication, *Integrating Science and Decision Making: Guidelines for Collaboration Among Managers and Researchers in the Forest Service*. This report proposes the following guidelines to facilitate such collaboration:

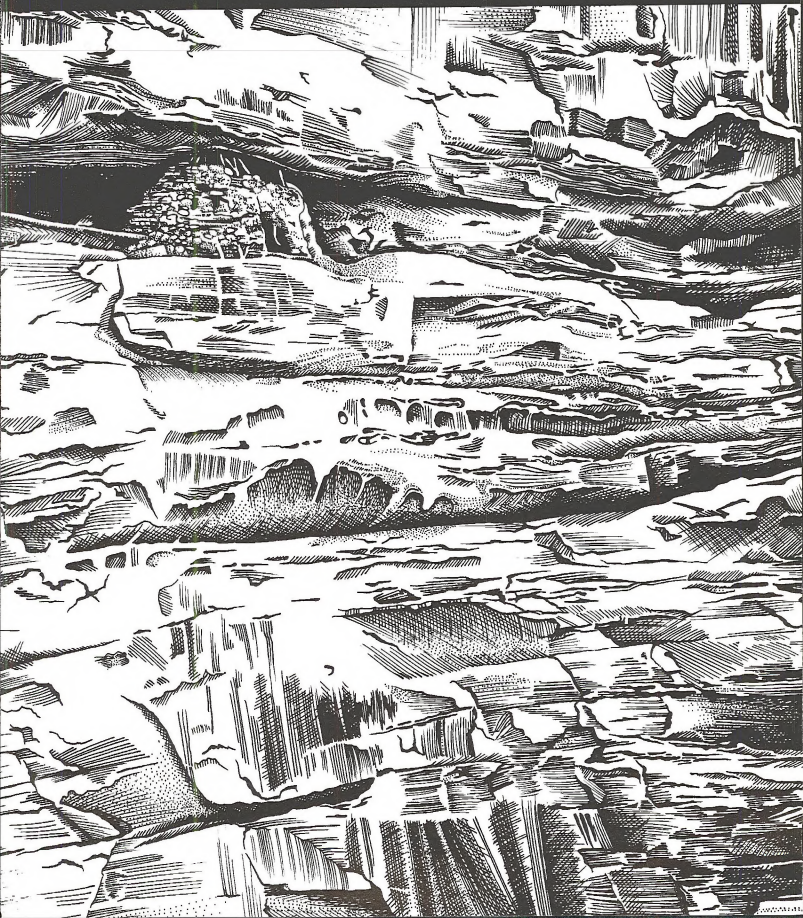
1. Build close personal relationships.
2. Understand cultural differences.
3. Pick the right person.
4. Invest in joint arrangements.
5. Collaborate for futuring.
6. Share responsibilities for identifying issues and involve researchers early and often.
7. Develop an organizational structure for collaboration.
8. Provide sufficient time and resources to address the issues that are identified.
9. Develop and implement a charter that commits research and management to address the issue.
10. Clearly identify roles and responsibilities.
11. Develop a communications, public involvement, and media plan.
12. Specify legal and policy constraints.
13. Capture lessons that are learned.

These guidelines are equally as relevant to the GSNEM as they are to any other natural resource unit or agency. Coupled with the special sense of place that so many attach to the Monument's lands, I agree with Secretary Babbitt when he says the development of the GSNEM as a science-based and science-friendly Monument provides an opportunity never before experienced. It promises to be something special—a true milestone in the history of natural resources management.

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ARCHAEOLOGY







Investigating Human Land Use Within The Grand Staircase-Escalante National Monument: The Roles of Archaeological Surveys

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ABSTRACT

Archaeology cannot be accomplished without theory or bias. Consequently, we, as archaeologists, must strive to make our theories explicit and to evaluate the effects various biases have upon our inferences. Many archaeological biases arise from received wisdom—what we presume to be true or to know about the past. Recent research has challenged some of our favorite beliefs and presumptions about Formative peoples who inhabited the Desert West, including:

- whether Pueblo I-III pitstructures were ceremonial kivas (con: Lekson, 1988, 1989; pro: Adler, 1993; Lyneis, 1996; Wilshusen, 1989; and many others; Stuart, 1991 discusses the periodic reoccurrence of pitstructures),

- Archaeologists researching the Anasazi have developed two conflicting views of the ancient Puebloan peoples who inhabited portions of the Grand Staircase-Escalante National Monument for more than 1,000 years. Some archaeologists propose that the Anasazi were primarily sedentary farmers who resided in substantial villages. Other archaeologists disagree, proposing that the Anasazi had a more mixed economy, involving seasonal movement between villages and temporary camps while they hunted, gathered, and cultivated both wild and domesticated resources. We discuss how biases in the available archaeological surveys contribute to this debate. These surveys have not been designed to address scientific questions, but instead have been shaped and defined to meet the needs of land managers and contemporary resource extractors. We must assess the effects of differences in land ownership, study boundaries, and contemporary land use upon survey data before we can confidently make inferences about the more ancient humans. Very critical evaluation of existing surveys must precede any use of the data for planning and managing the new Monument. No matter which view of the local Anasazi prevails, the rich archaeological record documents the long history of human land use within the Monument, challenging notions that the contemporary environment is a pristine wilderness, devoid of human presence.

- Anasazi abandonment of the Colorado Plateau due to drought (pro: Larson, et al., 1996; con: Dean, et al., 1996; Van West, 1994; too simplistic: Schlanger and Wilshusen, 1993),
- the significance of pottery types and quality (Simms et al., 1997),
- agricultural intensification and increased consumption of agricultural products over



time (as supported by settlement studies, pro: Larson et al., 1996; McFadden 1996; con: Lyneis, 1995; Van West, 1994; con, as demonstrated by human coprolites and bone chemistry indicating consumption of a mixed cultigen and wild resources diet without an increase in the proportion of cultigens: Chisholm and Matson, 1994; Cummings, 1995; Hegmon, 1996),

- the degree of political complexity and the nature of cultural boundaries (Geib, 1996; Hartley, 1991; Lightfoot and Martinez, 1995; Saitta, 1997; Speth, 1988; for the Virgin Anasazi, ranked: Rafferty, 1989, 1990; vs. more egalitarian: Lyneis, 1992),
- the influence of larger events, especially in Mesoamerica, upon local peoples (Wilcox, 1996),
- the roles of migrations and continuities (such as Numic spread, Anasazi origins and abandonments) in determining cultural variability (Dohm, 1994; Madsen and Rhode, 1994; Schlanger and Wilshusen, 1993; Talbot and Wilde, 1989), and
- degrees of sedentism and the coexistence of nomads in the vicinity of villagers (i.e., the notion of adaptive diversity: Nelson, 1994; Simms, 1986; Upham, 1984, 1988, 1994a,b; Young 1994a,b; but see critiques of Sullivan, 1987, 1994).

This list is by no means complete. Many of these topics deserve further consideration as research and management develops within the Grand Staircase-Escalante National Monument.

Our paper evaluates one form of archaeological bias—the effects of survey design upon our conclusions about human settlement and subsistence. We focus on human subsistence because this represents an aspect of the archaeological record that most archaeologists presume to be more readily knowable and less ambiguous than more abstract aspects of ideology or social organization. The existing

site data within and adjacent to the Monument has largely been collected in compliance with management needs and development interests (i.e., in advance of water, coal, timber sales, vegetation chaining, etc.). These data do not constitute a representative sample of the cultural resources and are biased by ownership and project boundaries. We demonstrate that subtle differences between surveys shape the data base and our claims about Anasazi subsistence. Uncritical compilations of larger numbers of sites and data from many different surveys do not necessarily eliminate the effects of survey biases and differences in methodologies. In light of our analysis, we propose that multi-stage, problem-oriented sample surveys be conducted within the Monument. The research designs guiding these surveys should challenge both received wisdom and gaps in our existing knowledge by collecting and analyzing data in ways more sensitive to human variability. Finally, we want to emphasize that the ancient Puebloan population of southern Utah exceeded the current population in and around the Monument. More than 11,000 years of residence in this region by the Puebloan people surely impacted and altered the local environment in ways that will be better understood as further research is accomplished within the Monument.

Virgin Anasazi Settlement-Subsistence and Diet

Two competing views have emerged for the settlement-subsistence and diet of the Virgin Anasazi who inhabited much of present-day southwestern Utah, northwestern Arizona, and southern Nevada from at least the early centuries A.D. until sometime in the 1200's (see Lyneis, 1995, 1996 for detailed culture histories). Bureau of Land Management archaeologists Dalley and McFadden (1988; McFadden, 1996; Walling et al., 1986), based on their excavations of substantial habitation (structural) sites in the lowlands of the St.



George Basin, and their surveys there and of portions of BLM-managed lands in the upper reaches of the Virgin River Valley, have argued the local Anasazi relied almost exclusively on agriculture. Larson et al. (1996) use survey data from the Vermillion Cliffs of southern Utah to argue for greater agricultural specialization within the Virgin Anasazi over time, leading to their inability to cope with the Great Drought of the A.D. 1270's and their abandonment of the region.

In contrast, Westfall et al. (1987), Lyneis (1995, 1996), and others propose that the Virgin Anasazi exhibited greater adaptive diversity, using a mix of hunting, gathering, and farming to obtain their subsistence. They suggest that more temporary camps resulted from periodic, probably seasonal, and perhaps longer term, exploitation of wild resources away from the habitation sites. In the lowlands of the St. George Basin and lower Virgin River, irrigation was necessary for agricultural production, so habitation sites were concentrated on and near the floodplain. The greater precipitation in the upper Virgin River Valley enabled Puebloan peoples to accomplish dryland farming at 5,000-7,000 feet. The upper limits were constrained by frost and the lower by insufficient precipitation (Lyneis, 1995).

This debate over the importance of agriculture and more substantial sites can be examined with settlement data recorded during the Muddy Creek-Orderville Watershed Project in western portions of Kane County. If the local Anasazi practiced a mixed economy, we should expect to find temporary camps and limited activity sites throughout the project area, with a higher concentration at higher elevations where dryland agriculture was not possible. If Dalley and McFadden (1985, 1988) are correct about the almost exclusive focus upon agriculture, then temporary camps and limited activity sites should be relatively rare, and settlement should be concentrated at lower elevations around agricultural (structural) sites.

As Upham (1994b) elaborates, many archaeologists presume that sedentary farmers

replaced earlier (Archaic) nomadic hunter-gatherers in portions of the Desert West. With Puebloan abandonment, farmers were replaced by hunter-gatherers or became more mobile again, as they gave up farming and increased their utilization of wild plants and animals. Thus, Dalley and McFadden (1985, 1988) also expect that most temporary camps and limited activity sites would pre- or postdate the Formative (Puebloan) farmers.

The Muddy Creek-Orderville Watershed Project

Portions of the upper Virgin River Valley were intensively surveyed during 1992-93 to document archaeological sites within the Natural Resources Conservation Service's (NRCS') Muddy Creek-Orderville Watershed Project (USDA NRCS 1995). This survey project is ideal for examining the debate over Virgin Anasazi settlement-subsistence, because the BLM inventoried 4,520 acres of Federal lands, while Utah State University (USU) used essentially the same survey methodology to inventory 5,315 acres of State and private lands. At a superficial level, what differed between the BLM and USU surveys was simply land ownership. Site data from both surveys are summarized by Fawcett (1994). USU surveyed 19 discrete parcels scattered from lower (5,400- foot) to higher (7,400-foot) elevations. Many parcels of State and private land surveyed by USU about those examined by the BLM.

Thirty-eight percent of the 60 prehistoric sites recorded by USU are Puebloan villages or structural sites with architecture, middens, and many potsherds. Most of them exhibit evidence of artifact collection and vandalism. Fawcett (1993) estimates that about 75 percent of the decorated potsherds that once existed on the surface of the villages have been removed by artifact collectors. Today, one is hard-pressed to find decorated sherds on most of the village



sites, making it difficult to estimate the chronological age and occupation spans. All of the village sites occur below 6,000 feet.

Larger projectile points, presumed to have been used with atlatls during the Archaic period (prior to the existence of the Formative villages), occur at 14 percent of the sites. Only a single site is believed to postdate the Formative and to be associated with more recent Paiutes.

More ephemeral limited activity sites tend to cluster around more substantial camps (see maps in Fawcett, 1994). Limited activity and campsites occur at all elevations, but villages are more restricted to lower elevations (Table 1).

Table 1. Distribution of sites by elevation.

Elevation (in feet)	Village	Long-Term Camp	Short-Term Camp	Limited Activity	Total
< 6,000	83 (62)	10 (22)	25 (29)	45 (51)	163
> 6,000	5 (26)*	21 (9)*	16 (12)	28 (22)	70
Total:	88	31	41	73	233

Chi-square = 50.8, d.f.=3, p=0.001 () Expected Value.

*Greatest differences between observed & expected values.

Data from: Fawcett, 1994.

Based on this survey data, Fawcett (1994) concluded that the Virgin Anasazi practiced a mixed economy in the upper Virgin River drainage. However, more recently, McFadden (1996) has used his analysis of the BLM and other survey data to continue to argue for greater reliance upon agriculture among the local Anasazi. How might differences in the ways our surveys were bounded and in terms of land ownership contribute to our debate about the importance of agriculture and substantial villages? A similar question can also be posed about the conclusion by Martin (1998) that the Virgin River Anasazi were always full-time agriculturalists: to what extent are his pollen, macrobotanical, and human skeletal samples biased towards substantial structural/village sites where evidence for agriculture would be expected to be more abundant? Evaluating hypotheses about variability in Anasazi diet requires samples from more marginal, temporary, and upland settings.

How Do Project Boundaries and Land Ownership Shape Conclusions?

The frequencies of the site types found in the BLM and USU surveys differ significantly (Table 2), despite the fact that we used similar survey methodologies and defined our site types in similar ways (villages—substantial scatters of artifacts with architectural remains and middens, long-term camps—scatters of previous plus nonarchitectural features, short-term camps—scatters of chipped and ground stone and sherds, limited activity—scatters of chipped stone and sherds).

USU's survey of State and private lands found more long- and short-term camps than expected, and fewer village and limited activity sites, while the BLM survey of public lands recorded more villages and limited activity sites (Table 2).

Table 2. Distribution of site types according to land ownership.

Survey (Land Owner)	Village	Long-Term Camp	Short-Term Camp	Limited Activity	Total
USU (State/private)	23 (26)	11 (6)*	15 (9)*	11 (19)	60
BLM (Federal)	64 (61)	10 (15)	15 (21)	55 (47)	144
Total:	87	21	30	66	204

Chi-square = 16.8, d.f.=3, p=0.000 () Expected Value.

*Greatest differences between observed and expected values.

Data from: Fawcett, 1994.

This finding surprised us. We generally presume in the Desert West that more elaborate and richer sites (including villages) are more abundant on the private land (Plog et al., 1978; Bettinger and Raven, 1986; Hardesty, 1986; Green, 1986; Becker, 1986; Sebastian and Larralde, 1989; Gilson, 1986). Settlers homesteaded or bought the lands with water sources, better grasslands, and more arable land, while the Federal Government retained what was left. The roughest and most remote areas often became BLM land.



Closer analysis suggests that we can probably attribute the differences between the USU and BLM surveys to subtle variation in the distributions of elevations within the areas covered by each survey (Figure 1). Only USU's survey examined the higher elevations on private land. Both surveys concentrated on lower elevations (< 6,000 feet) where village sites abound (Table 1), but only USU's survey examined very much acreage above 6,000 feet.

al., 1983). This survey also found far more utilization of upland settings than McFadden's (1996) BLM survey.

Insights for the Grand Staircase-Escalante National Monument

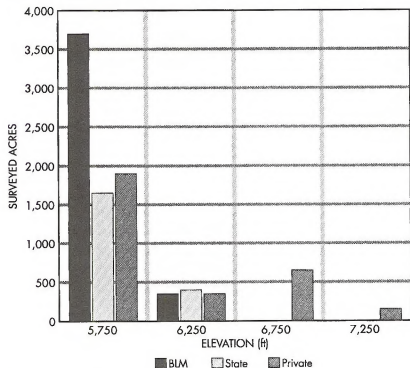


Figure 1. Acreage surveyed by elevation and land ownership.

By surveying more acreage at lower elevations, the BLM found slightly more villages (44 percent of 144 sites) than the USU survey (38 percent of 60 sites), and significantly fewer temporary camps and limited activity sites. Slight differences in the survey boundaries and coverage at different elevations created significant differences in the numbers and proportions of various site types between the two surveys.

The overall coverage of both surveys focused on lower elevations, exaggerating the numbers of village/structural sites. A sample survey of BLM lands in the upper Virgin River indicates that habitation/village sites only account for about 1 percent of the sites (Christensen et

In his summary of recent research within the Glen Canyon Recreation Area, Geib (1996; Geib and Fairley, 1998) also points to the similar ways that project boundaries and archaeologists' research interests have constrained and shaped our interpretations and knowledge.

Madsen's (1997) compilation of known archaeological data for 275 square miles of school trust lands within the Monument (2,700 square miles) located 60 cultural resource management projects and information about 116 sites. His estimate of 100,000 sites within the Monument and another 11,000 sites on trust lands may be too high because it is based on a presumed average density of 40 sites/square mile. Nevertheless, his estimate indicates that only a tiny fraction (1 percent) of the archaeological sites within the Monument are currently known.

Site surveys will be necessary just to document the range of variation among the archaeological remains within the new Monument. Funding limitations and the scale of this undertaking almost certainly dictate that these surveys be conducted over many years and involve formal samples. Because many data gaps and research questions must be addressed, the samples must incorporate multiple designs (variously using quadrats, transects, stratification, and



unit sizes), informed by specific data needs, logistical concerns, and questions. Our experience with the Muddy Creek-Orderville Project clearly demonstrates that great care is needed to eliminate, or at least control for, biases in our survey designs.

Considerable leeway should be incorporated into the cooperative agreements, contracts, and grants to fund these surveys to allow for the collection and analysis of data that challenges (rather than replicates) what we know about the past. The emphasis should be on describing and analyzing variability in human-created remains, and not on pigeonholing artifacts and sites into comfortable categories and timeslots. Micromanagement by contract officers hinders the creative scientific process. For example, the NRCS forbids the collection of artifacts, including obsidian, which would have been useful for hydration dates and source analysis. Test excavations that could collect radiocarbon samples were also forbidden. Thus, questions about chronology and contemporaneity could not be resolved.

Rather than using competitive contracting to produce more research that is unpublished and unreviewed by peers, and that is largely constrained by cost (lowest bid), we would encourage administrators to develop a consortium of interested researchers and publics. This consortium would prioritize research, help to allocate research resources, and provide peer evaluations to ensure that the high-quality and innovative research is accomplished. Publication, museum, conference, and other outlets for the research results should also be explored, including ways of disseminating the vast quantities of unpublished research materials already available for the region.

Finally, on a broader note, in linking archaeology to other natural and cultural resources within the Monument, we, as archaeologists, should emphasize that humans have inhabited the region for more than 11,000 years. Aboriginal populations peaked between A.D. 1000-1200 (Dean et al., 1996; Larson et al., 1996; Lyneis, 1996), at levels much higher than current population densities. Today, only a few thousand

people live in and around the Monument. At the peak (A.D. 1000-1200), the Monument probably held about 10,000-20,000 people. In the last century, some members of the public have removed vast quantities of artifacts from archaeological sites in southern Utah. Taken together, we cannot presume that either the Monument's environments or archaeological record are in any way pristine and lacking in human impacts.

Conclusions

Archaeologists want to provide definitive interpretations of peoples like the Anasazi who once inhabited most of the Colorado Plateau. As we have shown in this paper, simple things like how we define the boundaries of our study areas can significantly influence our observations and data. Minor differences in survey boundaries created significant discrepancies among the kinds of sites found between the BLM and USU surveys within the Muddy Creek-Orderville Project. The surveys differed in their coverage of different elevations within the watershed. The BLM survey concentrated on Federal lands, mostly at lower elevations, while USU examined State and private lands that included higher elevations. These factors created significant differences in the survey data between the two surveys. By not surveying more of the higher elevations, both surveys overemphasized the abundance of village/structural sites, and presumably the agricultural presence in the region.

Full coverage surveys (Fish and Kowalewski, 1990) of bigger or more comprehensive areas may not resolve the problem if we continue to define our sample universes as watersheds, or according to criteria arising from land ownership and management concerns. Many human processes and activities span much larger areas. For example, a long-fallow system may have operated over 3,600 square miles of the American southwest (Nelson and Anyon, 1996)—an area slightly larger than the Monument. Understanding the archaeology of such a region requires that we obtain



comparable samples over vast areas and involve many research partners. These samples must also be critically evaluated to determine how our methods and designs structure our observations and interpretations (e.g., Judge, 1981; Wobst, 1983).

The local Puebloan people not only lived in substantial villages and farmed, but also ventured into higher elevations to collect wild plants, hunt animals, and interact and trade with other people. They did not just react to the physical world, but worked to restructure it (e.g., Sullivan, 1996). Whether they intensified or increased their agricultural production over time remains problematic. At this point, it seems more likely that they continued to use a mix of resources and strategies.

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Archaeological Research in the New Monument: Lessons From Glen Canyon

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ABSTRACT

■ Establishment of the Grand Staircase-Escalante National Monument presents a wonderful research opportunity to expand upon our understanding of past cultures and human adaptations in southern Utah. Previous archaeological research in the region provides a general outline of cultural history, identifies significant research topics, and highlights gaps in existing knowledge. A comparatively well-studied portion of this region is the Glen Canyon National Recreation Area that borders the new Monument on its southeast and east sides. We review archaeological research in Glen Canyon to provide a context for suggesting potential research issues that might be addressed in the Monument and approaches that may be useful for studying the archaeological record. We close with a discussion of certain cultural resource management issues.

We were interested in presenting a paper at the Learning from the Land Symposium principally because of our involvement with a 5-year archaeological study in the Glen Canyon National Recreation Area (Figure 1) in the 1980's. From this study, we gained an understanding of regional prehistory and perspectives on archaeological research directions and cultural resource management issues for the recreation area. The relevance of this for the Grand Staircase-Escalante National Monument (GSENM) stems from both simple proximity and the comparatively intensive amount of archaeological research conducted in the recreation area. Glen Canyon borders the new Monument on its southeast and east sides, but more importantly, the canyon lowlands and adjacent higher elevation terrain contained within the Monument form part of a single ecosystem. Past peoples survived in this region by moving seasonally from lowlands to highlands and in between. Jennings and student archaeologists of the preinunda-

tion Glen Canyon Project (Jennings, 1966) recognized this. They realized that the archaeology in the canyons could not be understood without recourse to the adjacent highlands, such as the Kaiparowits Plateau.

Consequently, surveys and excavations were conducted in the highlands surrounding Glen Canyon, including the Monument. The reverse is also true. The archaeology in the highlands, which includes much of the Monument, is best understood by taking into account Glen Canyon prehistory.

The recreation area is also of relevance to the Monument because it has been far more intensively studied. Indeed, the foundation of what is currently known about regional prehistory largely stems from the Glen Canyon Project of the late 1950's and early 1960's. Later studies in the recreation area, especially the one that we recently completed (Geib, 1996a), have added to that foundation. The comparatively greater amount of work in Glen Canyon, particularly excavation, means that

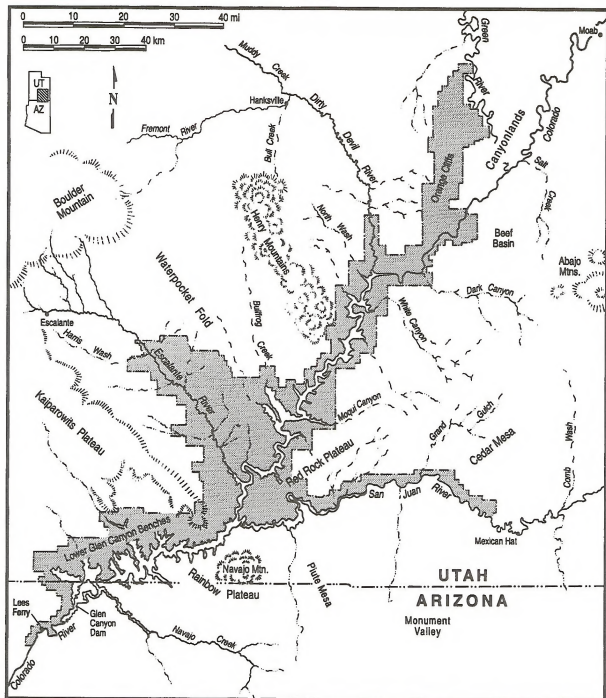


Figure 1. The Glen Canyon National Recreation Area in southeast Utah and northeast Arizona.

details of prehistory are far better known than in the GSENM. This knowledge base allows us to highlight data gaps and identify research topics potentially important to the Monument. We go on to discuss some management issues related to cultural resources.

The Glen Canyon National Recreation Area, for those unfamiliar with the region, consists

of about 1.2 million acres around the shores of Lake Powell. The recreation area generally includes a strip of land 5- to 10-km wide around the lake, but it also embraces a major portion of the lower Escalante River Basin and a substantial area along the western edge of Canyonlands National Park. The southern half of the recreation area is of particular relevance here for it abuts the Monument and forms



part of the seamless ecosystem that people exploited. The separation between the recreation area and the Monument is but a line on a map, meaningless when it comes to describing and understanding prehistory. As large mammals at the top of the food chain, humans require vast territories to survive. This is especially true for mobile foragers dependent upon nature's bounty, but it also applies to those tied to the increased productivity of small farm plots. Even when one's daily bread is obtained nearby, there are myriad reasons for big territories, everything from large game hunting to the collection of plants and minerals for religious purposes (Zedeño, 1997). Indeed, one of the benefits of the Monument is that it has a size and shape that should encompass much of the settlement diversity of past societies. This is not true of the Glen Canyon Recreation Area (or Capitol Reef National Park) because the Park boundary incorporates a long narrow slice of largely similar terrain along the Colorado River. Even the Monument, however, is probably too small, because the communities that inhabited the region likely exploited the high plateaus to the north and west and the canyon lowlands to the south and east.

Knowledge Gaps and Research Topics

The massive archaeological study conducted prior to the creation of Lake Powell contributed most of what is currently known about the Formative occupation of Glen Canyon and the Monument as well. Much of the archaeological data collected during the Glen Canyon Project pertain to ceramic period farmers, especially the most impressive portion of their record—cliff dwellings and open habitations. More recent studies have gone far towards filling some significant gaps in Glen Canyon cultural history, including the preceramic, preagricultural occupation of the region and the early portion of the agricultural period during which pottery technology was introduced.

Glen Canyon is now known to contain an excellent record of Archaic hunter-gatherers (Geib, 1996a), yet the initial portion of hunter-gatherer occupancy, known as the Paleoindian period, remains poorly documented. Diagnostic points such as Clovis and Folsom are known from a few places, but sites dating to this early interval are exceedingly rare (Davis, 1985, 1989). This is not solely a problem of over 10,000 years of erosion and deposition, though that is certainly important, but also one of archaeological recognition and amateur surface collection of diagnostics. Documenting a Paleoindian presence is one knowledge gap that could be addressed in the Monument. We have heard rumors of Paleoindian points coming from the Escalante Desert. Like it or not, efforts in this regard should involve local collectors who might already have considerable knowledge about where Paleoindian remains occur.

Considerably more evidence of Archaic period hunter-gatherers exists in and around Glen Canyon. Dart-size projectile points occur on many Glen Canyon sites, and thanks largely to the efforts of Holmer (1978, 1980) in the late 1970's, archaeologists can reasonably assign sites to the Archaic period based on points. Unfortunately, Archaic dart points are also a dwindling resource because of collectors. Some areas of Glen Canyon, and likely too of the Monument, have been stripped of projectile points. Projectile-point-based temporal assignments can be suspect for a variety of well-known reasons (changing point morphology from breakage and reworking, reuse of old points by later groups) and temporal specificity can be rather poor. Yet, many lithic scatters presently lack any other means for temporal placement.

Radiocarbon dates provide a more precise means for temporal placement, and fortunately, quite a few lithic scatters in Glen Canyon contain hearths. These provide a means to obtain dateable organics with comparatively little investment and disturbance, either during the survey or a small followup testing project. The testing and subsequent dating of hearths at



open sites in Glen Canyon and adjacent areas (Bungart, 1996; Bungart and Geib, 1987; Tipps, 1996) has greatly added to the regional chronology and expanded our understanding of Archaic settlement. Similar work in the Monument would likely be equally useful and would nicely complement that done in the surrounding lowlands. Experience has shown that excavating less than one-fourth of most hearths can recover sufficient carbon for standard dating. The recovery of macrobotanical remains, however, has proven difficult and may require substantially larger samples than the 2-4 liters so far analyzed. Perhaps though, the poor recovery is not because of preservation problems, but because few foods were ever carbonized in these features.

Radiocarbon dates can be used as a data set for examining intra- and interregional patterns in settlement organization, relative population, and other issues. A graph of all of the preceramic radiocarbon dates currently available from sites in and around Glen Canyon (Figure 2), reveals that this region of the southwest had a significant Archaic presence. Indeed, we expect that the Monument contains similar evidence of Archaic occupancy and has much to offer in our understanding of these foragers because the Monument provides a largely different set of resource opportunities than the Glen Canyon lowlands. The sharp contrasts provided by the pinyon-juniper forests and sage flats of the Kaiparowits Plateau, and grasslands and canyon oases of the adjacent

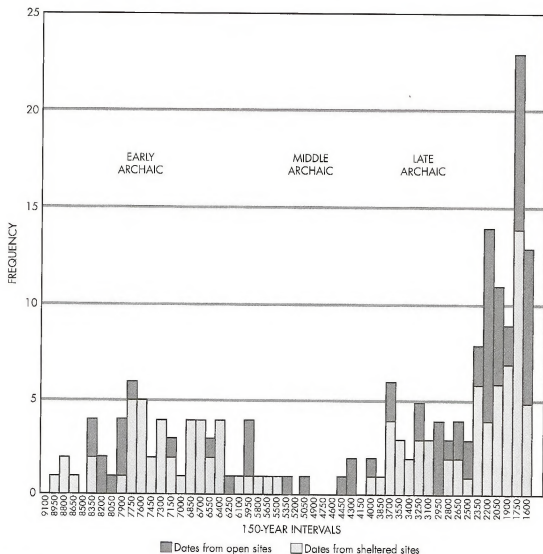


Figure 2. Frequency distribution of pre-1600 before present (B.P.) radiocarbon dates from sites in and around Glen Canyon using an interval width of 150 years (see Geib, 1996a for information on the dates).



Escalante Desert, provide an excellent setting to study Archaic period subsistence-settlement practices.

To the extent that the radiocarbon record is representative of population continuity, then the Glen Canyon region appears to have been continuously occupied by foragers from about 9,000 years ago up through the introduction of agriculture. There were, however, significant shifts in Archaic settlement patterns over the millennia as exemplified by changes in the use of specific places. Several caves located in the highlands surrounding Glen Canyon were frequently used as residential bases during the early Archaic period, resulting in substantial living accumulations. Between 6,000 and 7,000 years ago, however, the use of these shelters declined and ultimately they were totally abandoned or seldom used. The abandonment of previously important settlement nodes in the highlands seems to have been accompanied by increased use of well-watered settings in the Glen Canyon lowlands. Recently obtained dates between 5,000 and 6,000 years ago are mainly from lowland shelters situated near permanent water, including Benchmark Cave and the Hermitage, located in Lower Glen Canyon. Some middle Archaic sites in the Monument, however, are in settings that do not indicate a concern for locating near water (Tipps, 1998). We would expect to find some significant middle Archaic residential sites situated along the Escalante River and other riparian zones.

The patterning in radiocarbon dates shows that Glen Canyon was occupied during the time that corn and squash began to be incorporated into the forager lifestyle. The evidence at hand indicates that agriculture was adopted at different times by the inhabitants of the Glen Canyon region (Geib, 1996a). South and east of the Colorado River, initial use of corn and squash dates to at least 600 B.C. (Smiley, 1994, 1997). By 300 B.C., immediately south of Glen Canyon, there are small, semipermanent farming settlements characterized by pit-houses, abundant storage pits, and developed trash middens (Geib et al., 1995, 1997). In contrast, north and east of the Colorado River, such as in the Escalante River Basin, maize use

seems no older than the start of the Christian era (see review of evidence in Geib, 1996a). Also, north and east of the river, the impact of farming seems to have been less pronounced, at least at first, and a largely hunting-gathering lifeway evidently persisted far longer. The extent to which some groups living north and east of the river were reliant upon farming is an issue still needing investigation. McFadden (1996, 1998) presents evidence of Fremont dwellings situated in settings that are inconsistent with farming as a primary pursuit. The Monument is an important region for examining the process by which hunter-gatherers became farmers and for understanding variability in the degree to which a farming lifeway was adopted. Moreover, because sociocultural complexity evidently never reached levels attained in other portions of the Southwest, the Monument should prove important for analyzing the physical and cultural variables that gave rise to complexity. To obtain a broad understanding of causes, it is not enough to simply look in regions where complexity happened, such as in Chaco, but also in areas where it did not happen and ask why not?

A long-standing focus of research in Glen Canyon is the relationship between Fremont and Anasazi cultural expressions. Rock art is but one of the distinctions, albeit an important one, between the Fremont and the Anasazi. Figure 3 shows a panel of Fremont-style painted anthropomorphs in the lower Escalante River Basin. Other aspects of cultural difference include basketry, ceramics, and footwear. During the Glen Canyon Project, the temporal span of the Fremont was poorly known, with most age assignments based upon associated Anasazi trade wares. Because these suggested a post A.D. 1050 age, it was commonly assumed that the Fremont occupation of Glen Canyon was contemporaneous with the Pueblo II Anasazi occupation (Fowler, 1963; Lister, 1964). Therefore, Glen Canyon Project archaeologists concluded that two distinct ethnic groups occupied portions of Glen Canyon, including part of the Monument. Maps of the time show interdigitated fingers of Fremont and Anasazi culture, and discussions touched upon intercultural relationships.



Figure 3. Fremont-style painted anthropomorphs of the Dios Blancos panel in the lower Escalante River Basin. A worked stick under a rock cairn below this panel has a radiocarbon age of 1200 ± 80 years B.P. (Beta-21236, Geib and Fairley, 1992).

The true antiquity of Fremont occupancy in Glen Canyon was recently determined by dating maize from several Fremont sites of the Escalante River Basin. Maize samples from preceramic and early ceramic layers at such sites as Triangle Cave, Pantry Alcove, and the Alvey site, returned radiocarbon assays forming an unbroken sequence from A.D. 100 to 1000 (Geib, 1996a). When these assays are combined with other recently obtained dates from the Escalante River Basin, the overall impression of occupational continuity from late preceramic to early ceramic times is strengthened (Figure 4). There are no breaks in this series of dates or in the depositional layers at deeply stratified shelters such as the Alvey site that might be construed as a population hiatus. The one new item of material culture that appears during this sequence is pottery, sometime between A.D. 400 and 500. The material culture associated with these dates is largely distinctive from that present to the south and east of Glen Canyon at this same time, and most archaeologists would

classify it as Fremont. One of the dates, with a midpoint just under A.D. 900, is on a worked stick associated with the striking pictograph panel of anthropomorphs shown in Figure 3 (Geib and Fairley, 1992). The panel has no parallels in Anasazi styles of the same time to the south and east, but has definite similarities to rock art panels to the north and west.

Given this recent chronological resolution, it seems evident that early ceramic Fremont occupancy of the Escalante River Basin was an outgrowth of an *in situ* preceramic occupation that, since at least A.D. 100, was partially dependent upon farming. Prior to about A.D. 1050, there was no intermixing of Fremont and Anasazi cultures in Glen Canyon as proposed during the Glen Canyon Project; instead, Fremont culture alone predominated north of the Colorado River. After about A.D. 1050, there was a significant change, and the area previously occupied by the Fremont was intruded, if you will, by the Anasazi. The precipitating factors and processes behind what

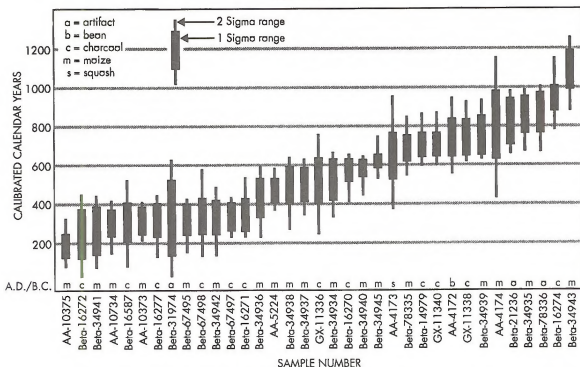


Figure 4. Array of calibrated radiocarbon dates from the Escalante River Basin demonstrating occupancy of the area from late preceramic to early ceramic times.

appears to have been a significant shift in claimed territories with perhaps interethnic competition needs additional study. Fairley's (1997) suggestion of Anasazi expansion into favorable cotton farming areas is worth serious consideration. It still seems credible that the large site at Boulder represents an Anasazi intrusion into this productive highland setting, but this needs additional study. More importantly, the thorny theoretical problem of how prehistoric ethnic and social groups are represented in the archaeological record needs to be tackled. The Monument presents a fine setting for examining whether and to what extent ethnic affiliation is inferable from archaeological remains.

The late Prehistoric period is still a large unknown. Probable Paiute sites occur in various places of the Glen Canyon region, but virtually none of these sites have been studied in any detail or been dated. A circa 1300 A.D. date on a brush structure of the Escalante River Basin (Geib and Fairley, 1992) is a tantalizing piece of information and there are other scattered bits of evidence. These have yet to be integrated into a coherent picture of what

took place from A.D. 1300-1800. The brush structure date suggests that hunter-gatherers reoccupied the Glen Canyon lowlands on the heels of the departing Anasazi. The Monument is known to have been the homeland for one band of Southern Paiute (Kelly, 1964). What is the earliest trace of this group within the area, and how do ethnographic data relate to archaeological evidence? We could detail other general and specific research issues or data gaps relevant to the Monument, but space is running short and we would like to touch upon some matters that relate to management.

Management-Related Issues

The extractive nature of archaeological fieldwork means that past collections and records are essential to the productive investigation of prehistory in any region. This is all the more apparent in a place such as Glen Canyon where so much of the archaeological record was totally destroyed. In Glen Canyon, we no



longer have the luxury of returning to some 2,000 sites to pursue new lines of research. We must turn to the records and collections made by past researchers and hope that they are up to the task. Old collections and records inherently impose certain limitations and they may not be ideal for every question, but they are vital to furthering our collective knowledge. We must never forget that the field notes and collections made today, even from the most obscure sites, will someday be consulted by other archaeologists. Fortunately, the Monument should not experience a Glen Canyon-scale loss of cultural resources, yet certain classes of sites have already been largely lost to science because of looters. Dry shelters in particular have been severely damaged and the evidence obtainable from shelters is not duplicated at open sites. Perishable remains, both artifactual and nonartifactual, allow the investigation of topics that could not otherwise be examined.

We can illustrate the value of old collections with one example from Glen Canyon, that of Benchmark Cave, a site located in Lower Glen Canyon. The 1962 excavation of the cave exposed over 4 m of cultural fill (Figure 5) and recovered many remains, including sandals. This deep stratigraphic sequence was interpreted as resulting from rapid deposition without

long-term breaks over the span of just 100 years during Pueblo II (Sharrock, 1964). The recent radiocarbon dating of portions of plain weave sandals from the cave disclose a different site history. A sandal from stratum 5 is 5,800 years old, whereas a sandal each from strata 10 and 12 are 3,300 and 3,200 years old, respectively (Geib, 1996b). The 1.5 m of cultural fill separating stratum 5 from stratum 10 represents considerable Archaic deposition in the cave. Rather than having just Pueblo II remains, we now know that Benchmark Cave had a significant record of forager accumulation extending back at least 6,000 years. If it were possible, another round of excavation would be called for at this site, and certainly the existing collections deserve additional study in light of these new dates.

The lessons from this one example extend beyond the value of old records and collections. They also highlight that we can never know at the time of collection what types of research questions might eventually be asked, what types of new analytical techniques will be developed that will enable new questions to be answered, and how new paradigms change the values of cultural resources. It seems that Glen Canyon Project archaeologists had on blinders when it came to recognizing Archaic

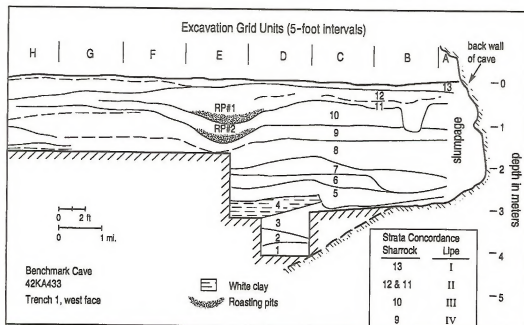


Figure 5. Stratigraphic section of Benchmark Cave in Lower Glen Canyon. Modified from the profile prepared by Dave Read and Floyd W. Sharrock and housed at the University of Utah.



remains. Their abiding interest in Formative remains and an evident hypercaution with attributing any remains to earlier cultures resulted in sites such as Benchmark Cave being misinterpreted and understudied. It is important to ask what blinders do we still wear? What evidence are we overlooking now? What sites are we writing off as insignificant or redundant because we do not take the long-term view of scientific research? There was a time when archaeologists used roof timbers from sites for fuel wood. The foolishness of this practice is obvious today, but what analogous practices still occur?

There is a tendency these days to shy away from surface collection during recording. This is perhaps partly a consequence of preservation thinking—the belief that it is better to preserve cultural resources in place. The high cost of curating collections is certainly another motive. It is easy to challenge this practice based on experience in the Glen Canyon Recreation Area, because every year visitors remove a volume of material, from sherds and points, to corncobs, and even mundane items such as flakes. For whom are we preserving surface remains? For science and the public at large or for individuals to selfishly pocket an artifact or two? There are visitors who would never think of sticking a shovel in the ground at a site, but who nonetheless collect projectile points and sherds. The initial recording of a site may be the only instance when temporal diagnostics can be saved for future research.

As the history of archaeological study in Glen Canyon illustrates, the issues and questions that will interest future researchers and visitors are unpredictable. It is equally impossible to know what technical and theoretical developments may allow us to investigate aspects of the past that are presently unapproachable. For this reason, it is important that land managers keep an open mind to the potential value of what today may seem like insignificant or uninteresting archaeological resources. We may naturally focus on the largest, most complex, or most scenic prehistoric sites, and these qualities tend to attract the most attention from the casual visitor. It is essential,

though, that the full spectrum of archeological remains be considered in future preservation and management plans. This includes diffuse lithic scatters, isolated bedrock grinding slicks, single course rock enclosures, and individual pot caches.

The National Monument designation ensures that the area generally, and some sites specifically, will attract an increasing number of visitors in the future, and the interests and impacts of those visitors may significantly differ from those of the past. With increasing numbers of recreational users, land managers need to identify those areas and sites likely to attract the most attention, and then establish a plan for dealing with the inevitable impacts. A component of this plan may include cyclical monitoring of sites to ensure that unacceptable levels of impacts do not occur. Yet, monitoring by itself is not a form of treatment, nor a substitute for active management. Monitoring should be done with a well-defined and funded program in place for dealing with observed impacts. Monitoring in the absence of a well-thought-out plan that sets indicators, standards, and protocols for dealing with unacceptable levels of change is simply a waste of time and money.

Similarly, if management decisions deliberately or incidentally increase visitation to certain archeological sites, then monitoring should not be substituted as a form of mitigation. A monitoring program is not needed just to demonstrate yet again that sites subjected to constant visitation lose their integrity over time. Rather, when managers make decisions that result in increased visitation, then the inevitable impacts to those resources must first be mitigated through careful surface documentation or excavation, just as existing laws mandate us to do for other kinds of development. Promoting visitation to an archeological site, even by well-educated, sensitive visitors, will inevitably result in damage to that site. Stabilizing a site after damage has occurred, or stabilizing a site to withstand future visitation without first recovering information, is likewise unacceptable.



Conclusion

Historic trails in Glen Canyon were often built upon the routes pioneered thousands of years earlier, such as where a Navajo stock trail follows, but improves upon, the course that the Anasazi took a thousand years earlier. Likewise, we have attempted to build upon the accomplishments of the Glen Canyon Project, revising earlier interpretations as necessary to better accord with new evidence. This process of reanalysis and reinterpretation is common to all science. Archaeological research is an unending cycle of study and interpretation, restudy and reinterpretation, that brings us ever closer to a more accurate description and understanding of the past. Archaeological research in the new Monument doubtless will follow this same pattern. Research may be unending, but unfortunately, the source of archaeological data is finite. Every year the number of sites available for study decreases because of both natural and human disturbances. To the extent that the Monument serves to slow the loss of archaeological remains, then its creation can be deemed a success. More importantly, creation of the Monument affords the opportunity to initiate studies that are not development-driven, but designed with research in mind rather than the exigencies of compliance. Such studies should build upon past research and pioneer new routes for the future. They should concern cultural resources in the Monument as a whole, and their relation to cultural resources outside the Monument. Beyond the basic goal of documenting the history of human endeavor in this one part of Utah, archaeological research in the Monument should help to illuminate general patterns in human evolution and adaptation.

The Monument should prove an excellent setting for the archaeological study of hunter-gatherers and small-scale horticulturalists. The archaeological traces of these peoples are numerous and varied. There is exceptional preservation of subsistence remains and perishable technology within stratified dry

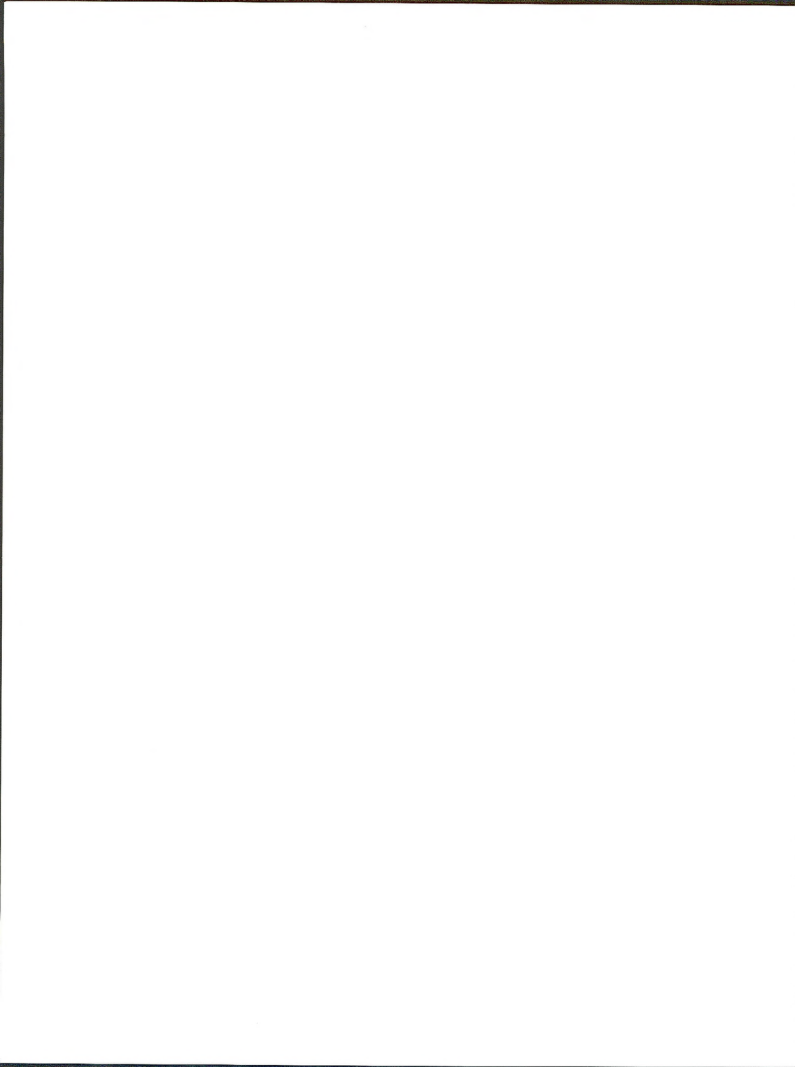
shelters. The corpus of rock art is rich and dates back to at least the middle Archaic. Paleoenvironmental data abound from a variety of sources and should eventually enable detailed climatic and biogeographic reconstructions for the late Pleistocene and the entire Holocene. To make the most of the still-rich archaeological data base, managers should initiate a long-term, Monumentwide research effort toward documenting not only the common lifeway patterns that form the basis of cultural history, but the variability that informs us about the organization of hunter-gathering and simple farming societies and how they change. Such an effort should involve a multidisciplinary approach and should seek the active involvement of Native Americans.

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Learning to Preserve and Preserving to Learn: A Case Study in Grand Staircase-Escalante National Monument Archaeological Research

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In 1876, geologist Clarence Dutton crossed Boulder Mountain, looked east toward Capitol Reef and the Henry Mountains and south across the Circle Cliffs and the Escalante River Basin, and declared:

"It is a sublime panorama. The heart of the inner Plateau Country is spread out before us in a bird's eye view. It is a maze of cliffs and terraces...red and white domes, rock platforms gashed with profound canyons, burning plains barren even of sage—all glowing with bright colors and flooded with blazing sunlight....It is the extreme of desolation, the blankest solitude, a superlative desert" (Dutton, 1880).

ABSTRACT

■ During the late spring of 1997, archaeologists from Brigham Young University carried out limited archaeological research at an important Anasazi site located in the Circle Cliffs within the new Grand Staircase-Escalante National Monument. The research complements ongoing research in nearby Capitol Reef National Park, seeking specifically to understand when the Anasazi occupied this region, how they adapted to the local environment, and their relationships with contemporaneous Anasazi groups to the west and south and with Fremont peoples to the east and north. Although limited in scope to a single site, the project demonstrates the research potential available from the wealth of archaeological sites within the Monument boundaries and the variety of issues that can be addressed. This paper summarizes both the Capitol Reef and the Lampstand projects and our perceptions of the usefulness of this research to the scientific community, to the Monument Planning Team and land managers, and to the public. We will also outline some possible short- and long-range goals for archaeological protection, preservation, and study within the Monument.

This same desolation and solitude of the lands now incorporated into the Grand Staircase-Escalante National Monument (GSENM) have been a boon to preservation of countless prehistoric archaeological remains.

The Brigham Young University (BYU) Department of Anthropology and Office of Public Archaeology recently completed the second field season (of an anticipated 5-year program) of archaeological survey and testing in Capitol Reef National Park (CRNP), which borders the northeastern edge of the new GSENM, and includes small portions of the Circle Cliffs. Obviously, these modern



administrative boundaries are irrelevant when considering prehistoric land use strategies, and the CRNP work, like that in nearby Glen Canyon, has direct application to scientific study within the Monument. Recognizing this, our CRNP research design, written well before the GSENM was announced, proposed limited work at Lampstand Ruins, a large, late Puebloan residential site in the northern Circle Cliffs (outside the Park, but within the GSENM). This work was designed to test the applicability of regional models of land use, such as that proposed by Geib (1996). Lampstand was a logical choice for testing, since structural sites like Lampstand are apparently absent in the park.

This paper reviews research findings from the 1996 survey in Capitol Reef and limited excavations at Lampstand Ruin carried out in the late spring of 1997. The data gathered during the 1997 survey work in the northern part of Capitol Reef seems less relevant to the issues here so is not included. We also discuss the significance of our CRNP and Lampstand work to the scientific community, to the Monument Planning Team and land managers, and to the visiting public. We will then present some views on archaeological research and resource preservation in the GSENM.

The Capitol Reef Project

Research Focus in Capitol Reef

As might be expected on a large project, stated research issues were general at the onset and are being refined as we become better acquainted with the region and the kinds of cultural resources present. Themes range from paleoenvironmental reconstruction to settlement patterns and chronology. CRNP and the general Fremont River vicinity, of course, were where Mors (1931) recognized and defined the Fremont as distinct from the Anasazi. Naturally, therefore, our research interests are somewhat biased toward better defining the Fremont and Anasazi occupations within the Park and in the region.

1996 Field Season

During the 1996 field season, BYU surveyed about 4,400 acres within 8 of 10 systematically placed transects and four judgements defined blocks (Richens et al., 1997) (Figure 1). The transects were spaced at 3-mile intervals, beginning at the south end of the Park and stretching to a point just north of the Bitter Creek Divide and directly east of the northern end of the Circle Cliffs. Surveyed areas included three general environmental zones (in part following Geib, 1996): 1) lowlands, including the barren flatlands and low mesas and reefs of the Halls Creek drainage, 2) midlands, including the steep and rugged slickrock domes and gorges of the Waterpocket Fold and other rugged slopes between the mesas and the canyon bottoms, and 3) uplands, including the pinyon-juniper-covered table lands such as the mesas at the top of the Fold and the interior of the Circle Cliffs. This southern part of the Park is acutely lacking in available water. Besides Halls Creek, which is only permanent from the Halls Creek Narrows southward, there are few springs. There are, however, the numerous waterpockets or tinajas that dot the Waterpocket Fold and are the namesake for this dominant formation in Capitol Reef. Elevations vary from about 4,000 to 7,200 feet.

Survey Findings

One hundred fifty-seven new archaeological sites (14 multicomponent) were recorded in the southern section of the Park, adding to an existing data base of sites mostly located along the Burr Trail or the Notom Road. Included are 25 historic components and 168 prehistoric components (22 Archaic, 20 Fremont or Anasazi, and 9 Late Prehistoric, and 117 components of unknown age). All historic sites are related to small-scale ranching and farming activities or recreational use. Prehistoric site types, on the other hand, are varied and include quarries, lithic scatters, camps, and habitation sites in both open and sheltered contexts. Seventy five percent of all sites were found at elevations between 4,500 and 6,000 feet.

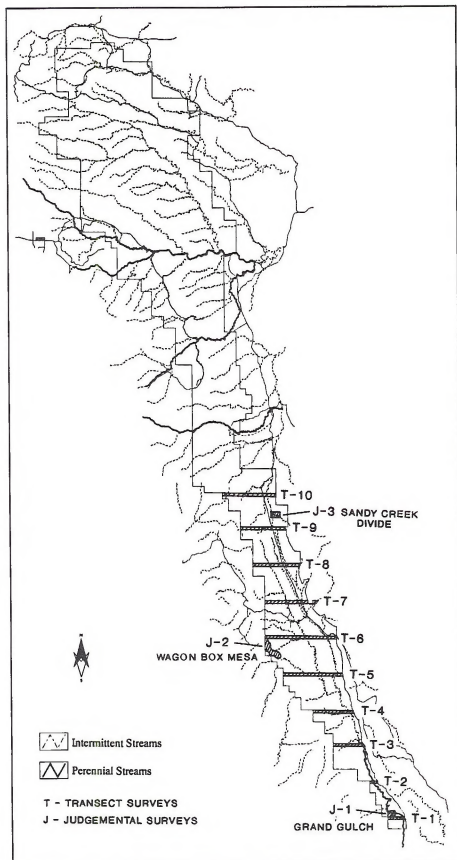


Figure 1. Transects selected for survey in the southern portion of Capitol Reef National Park.

Environmental zones are very telling as to land use for all historic and prehistoric periods. In the lowlands, which represent our largest sample, site density in the low, alluvial flats of upper Halls Creek drainage is low to moderate. However, in lower Halls Creek, the valley narrows considerably so that barren lands are minimal and site density increases. As Halls Creek valley widens to the north, sites are concentrated along the valley edges. In part, this is due to the heavy exploitation of extensive exposed veins of medium- to high-grade cherts eroding out of the Upper Morrison Formation. Site density close to or within the Waterpocket Fold was very heavy, particularly throughout the numerous deep canyons cutting through the Fold, but also on low prominences overlooking Halls Creek. For example, the low dunes and ridges fronting the numerous slot canyons on the east side of the Fold, both north and south of the Burr Trail, contained almost a continuous scatter of cultural material.

Portions of the midlands are steep and rugged, with large areas of slick-rock. Site density is at least moderate in many areas where the rugged areas level out. Canyons



that access the top of the Fold, such as the Muley Twist, were particularly heavily utilized; likewise, the many tinajas and the few springs, many of which lie in this midland area, were popular prehistoric camping spots.

The third environmental zone is the heavy pinyon-juniper-covered uplands that include the mesas within and adjacent to the Circle Cliffs. This area was also impressive in site density, although less so than the lowlands. Here we found extensive lithic scatters covering large areas of mesas and ridgetops, and along the numerous small drainages. Our sample takes in only the eastern edges of the northern Circle Cliffs, and does include much of the interior of the Circle. In transects T-9 and T-10 and on Wagon Box Mesa, large, impressive sites spread out across the top of the Fold. These sites are in dense pinyon-juniper, overlooking the Circle Cliffs, and afford access in a few spots down into the interior of the Circle Cliffs.

Generally, it appears that this southern one-third of CRNP was very heavily utilized throughout the Prehistoric period, although somewhat less so during the Late Prehistoric.

Testing Results

Testing focused on alcoves in slot canyons along the eastern edge of the Fold and open sites both in the Fold and in the pin on-juniper zone. The alcove deposits were well-preserved,

as some sediments are at least moderately rich and deep. Many of the open sites have ash stains visible on the surface. Limited testing in some of these proved the ash to be very shallow, suggesting the site surfaces have been badly deflated. However, testing of two extensive ash stains at a large open site in the Oyster Shell Reef (42WN4001) revealed two pithouses, one dated to 79 B.C., and the other to A.D. 635 (Table 1).

The limited information on prehistoric subsistence came from sites that might be either Fremont or Anasazi. Several small alcoves contained either storage pits or remains of corn, beans, and squash. Corn from one alcove site in a slot canyon south of the Burr Trail dated to the A.D. 900's. Corn collected this summer from a small granary in the central part of the Park dated to A.D. 665. The information we have to date supports lowland farming in the region by both groups, and dispersed settlements.

Two other sites were dated during the 1996 work: a small hearth (42GA3954) on a dune at the mouth of one of the slot canyons (A.D. 1443-1954); and a large ash stain in the pinyon-juniper (42GA3987) in the northeast portion of the Circle Cliffs (390 B.C. - A.D. 20).

We are awaiting macrobotanical data from Late Prehistoric and Archaic sites' subsistence. As mentioned, Archaic groups seem to have

Table 1. Radiocarbon dates from Capitol Reef - 1996 field season.

Site No. Sample No.	Provenience	Material*	Radiocarbon Years	Calibrated Range-2 Sigma	Calibrated Range-1 Sigma	Intercept
42GA3954 Beta-101266	eroded hearth, 2.5 cm bgs	pooled juniper, Cawania	300+70	A.D. 1443-1954	A.D. 1482-1660	A.D. 1686
42GA3987 Beta-101267	middens-like stain, 12-22	pooled juniper, pine cm bgs	2180+80	390 B.C.-A.D. 20	357-49 B.C.	181 B.C.
42GA4001 Beta-101269	pit in pithouse floor	pooled juniper, pine	1460+60	A.D. 537-682	A.D. 595-660	A.D. 635
42GA4001 Beta-101268	pithouse floor contact	pooled juniper, pine, Ephedra	2120+60	349 B.C.-A.D. 60	182-8 B.C.	79 B.C.
42GA4063 Beta-101263	surface of alcove	corn	1350+70	A.D. 727-1026	A.D. 871-997	A.D. 922

*All charcoal unless otherwise noted.



been less preferential in their use of both lowlands and higher elevations than the later groups.

A Developing Model of Land Use in the Capitol Reef/Circle Cliffs Region

The survey and testing work to date combined with ethnographic data and previous research enables us to begin formulating general models of human use of the region. Two models are described here.

Hunter-Gatherer Model

A traditional model for hunter-gatherers can be derived from Kelly's (1964) ethnographic work with the Southern Paiute (research also part of the Glen Canyon study). Kelly places a few families of Kaiparowits Paiute in the Circle Cliffs area just west of the Park. Her work suggests that hunter-gatherer strategies consisted of small groups with high residential mobility, finely tuned to varying resources. Archaeological residues from groups practicing such a strategy would include many small residential sites scattered across the landscape. This strategy is assumed to include Archaic, Late Prehistoric, and Ute/Paiute peoples.

Farmer Model

Modeling farmers is more complex, and at least three models are possible. A traditional model for farmers emphasizes logistical organization to accommodate gardening demands, while maintaining some level of exploitation of wild foods. This model could take two forms: 1) farmers living and cropping in the lowlands along Halls Creek (which seemed a great leap for us to

assume, as it was for Lister, since Halls Creek is not perennial north of the Narrows) and making logistical use of the uplands, or 2) farmers living in the uplands with logistical use of the lowlands, including the resources along Halls Creek and other locations in the Park [as proposed by Geib (1996) for the Pueblo II period in Glen Canyon]. Geib also suggests a third model: diffuse settlement of the lowlands by small family groups unrelated to the larger village sites.

Discussion

Although we are still processing data and the numbers of sites with cultural affiliation are small, preliminary observations about area prehistory, and particularly about land use strategies, can be made. The distribution of Archaic and Late Prehistoric components was used to test the hunter-gatherer model. Archaic occupations are rather evenly distributed across all elevations surveyed, a pattern that seems to fit the hunter-gatherer model quite well (Figure 2). The distribution of Late Prehistoric period sites (also hunter-gatherers), however, is less convincing and, in fact, resembles the Formative distribution, although no sites with visible architecture or developed middens clearly dating to the Late Prehistoric period were found. The number of Late Prehistoric sites is so small, however, that no conclusions can be drawn.

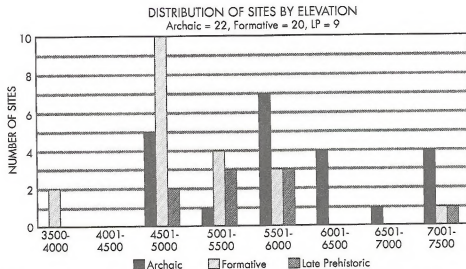


Figure 2. Distribution of sites by cultural affiliation and elevation in the southern portion of Capitol Reef National Park. Only includes sites recorded by BYU during the 1996 field season.



The distribution of sites with Anasazi or Fremont diagnostics contrasts with the Archaic in that the range of elevations at which they are found is limited even without considering function (logistical vs. residential). Farming period sites are typically situated between about 4,000-6,000 feet. Of course, the presence of sites like Coombs Village, Schoolhouse Ruin, and the Lampstand Ruins, all support the second farming model. However, the discovery of two pithouses, one with limited masonry associated with it, and the other apparently without masonry and likely constructed of perishables, is intriguing. Importantly, both appear to predate the large structural sites in the uplands and could provide support for the third strategy operating at an earlier date.

Our desire to test these models further led to the research at the Lampstand Ruins described below.

Testing and Mapping of Lampstand Ruins

The Lampstand Ruins include three distinct roomblocks and various smaller features (see site numbers on Figure 3). Two of the roomblocks are on the eastern end of a high mesa top separated by a narrow passage. Immediately below the mesa rim, on the south side, are the remains of several structures, probably small granaries, but including other larger features. The third roomblock is on a pinyon-juniper-covered flat below and north of the mesa. Below and south of the mesa is a boulder field. Much of this area is covered with a light scatter of cultural material and rock alignments suggesting temporary use facilities are associated with several of the larger boulders. During the late spring of 1997, the BYU

archaeological field school carried out test excavations and mapping at these ruins. To our knowledge, prior to our testing, no formal work had been carried out at Lampstand beyond site recording.

Research Interests and Objectives

Our goals were to: 1) *document* the site by mapping all features that make up the Lampstand complex, 2) *date* the site use to assess contemporaneity of the various features and roomblocks in the complex, 3) obtain *subsistence* information, as very little quantified data is available on subsistence for the Anasazi sites in the region, and 4) describe and analyze the *material culture*. Two data sets of particular interest were ceramics and chipped stone, as these were perceived particularly useful in testing whether the Lampstand occupants were visiting and exploiting resources in Capitol Reef National Park to the east.

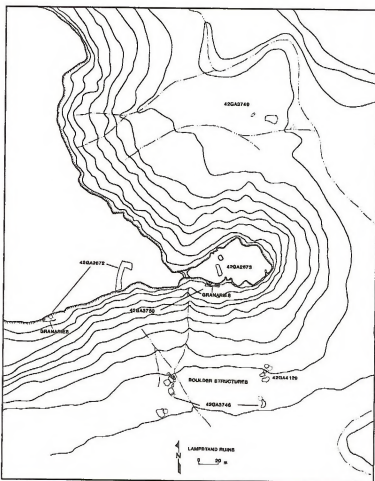


Figure 3. Plan map of the several Lampstand Ruins.



Mapping and testing was carried out during the first part of June 1997. During that time, individual crews worked on each of the roomblocks and in the boulder structures.

Testing Results

Lower Ruin (42GA3749)

The most extensive excavation was in the northern roomblock, an area previously disturbed by vandals. On the surface there appeared to be one central, but small and partially disturbed, masonry roomblock. Several meters to the southeast were the remains of a slab-lined feature that had been almost totally destroyed. To the west was another, smaller masonry roomblock that had also been vandalized. We selected the central roomblock for exploration (test areas 1 and 2) (Figure 4).

We uncovered two rooms in the central roomblock: a masonry storage room with low walls and evidence of a flagstone floor, and, adjacent to it on the west, a larger, jacal-walled room. It most likely served as a residence, but it had been only lightly used and lacked a

hearth. Testing in the badly disturbed feature to the southeast found the remains of a subsurface pit that probably was slab-lined. Another test pit south of the central roomblock probed a probable midden area with moderate to high densities of artifacts, charcoal, and some faunal remains.

Upper Ruins (42GA2672 and 42GA2673)

Testing in the westernmost ruins (42GA2672) on the mesa top consisted of two 50-cm by 50-cm pits in the open areas, a long trench east of the main roomblock, and a single test pit in the center of one of the rooms. The former testing indicated relatively shallow deposits, but with evidence for intact extramural features. The test in the room revealed surprisingly deep and undisturbed deposits below dense wall-fall. The fill interior was also heavily burned and contained abundant ceramics and some ground stone and bone tools.

The only testing near the east roomblock (42GA2673) was a single 50-cm by 50-cm test pit in what we thought was a shallow

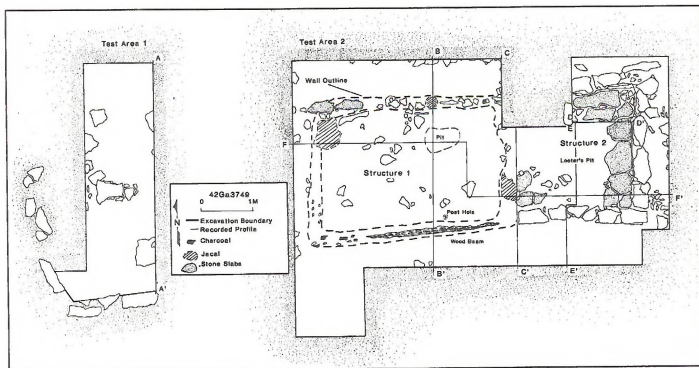


Figure 4. Detailed plan map of test areas 1 and 2 at 42GA3749.



midden area several meters east of the masonry unit. However, in that test pit, we partially exposed a slab-lined feature, and it is possible that the deposits are deeper and more extensive in this and nearby areas than the surface materials seem to indicate.

Dates

Radiocarbon dates from various features range in age from A.D. 700 to A.D. 1200 (Table 2), a long timespan for what we initially assumed to be a comparatively short-lived occupation. Ceramic counts and percentages are not yet available, but types present include Tusayan black on red, Moenkopi corrugated, Sosi and Dogoszhi black on white, Black Mesa black/white, and gray wares. Moenkopi corrugated Coombs variety is present and Coombs variety for other types may also be present. These types were found in the upper ruins as well as the midden at 42GA3749. These same ceramic types are dominant at Coombs, and indeed the two sites appear to be contemporaneous (Lister et al., 1961). The two latest dates agree with the ceramics, placing site occupation in the late A.D. 1000's and A.D. 1100's.

Discussion

The several analyses from Lampstand are only now underway, and it will be awhile before we can state more clearly our success in reaching our research goals for the site. We can say that information on subsistence, specifically animal bone, was very sparse, as were chipped stone tools and debitage from excavations. Obviously, the work adds to an otherwise limited, and biased, data base on Pueblo sites from the northern Circle Cliffs. We suspect that there is a tie between this and other northern GSENM sites and those in the Waterpocket Fold. The availability of high-quality chert in numerous veins throughout the Fold and vicinity suggests these areas were accessed at least for that reason. Perhaps more significant, however, is the evidence of use of the Fold as a major travel corridor by Fremont and Anasazi groups. There appears to be mixing of sites from both groups in the southern end of the Park, and site densities are particularly heavy in the few areas where the Waterpocket Fold can be crossed with some semblance of ease. These areas are very close to Lampstand, and we should not be surprised to find additional connections between the two areas.

Table 2. Radiocarbon dates from the Lampstand Ruins - 1997 field season.

Site Number	Sample Number	Material*	Provenience	Years BP	Calibrated Range- 2 Sigma	Calibrated Range- 1 Sigma	Curve Intercept**
42GA2672	108490	pine, juniper	Roof fall layer, 52 cm bgs	970±60	A.D. 980-1215	A.D. 1010-1165	A.D. 1035
42GA2672	108491	juniper	Ash stain within test trench, 8 cm bgs	1060±50	A.D. 885-1035	A.D. 970-1020	A.D. 995
42GA3749	108492	Ephedra pine, juniper	Ash-stained midden, 30-40 cm bgs	1300±60	A.D. 645-880	A.D. 665-785	A.D. 695
42GA3749	108493	pine, juniper	Ash-stained midden, 40-50 cm bgs	1220±60	A.D. 675-975	A.D. 720-885	A.D. 800
42GA3749	108494	pine, juniper	Ashy sediments overlying a wall, 14-19 cm bgs	890±70	A.D. 1010-1275	A.D. 1035-1235	A.D. 1175
42GA3749	108495	pine, juniper	Ashy sediments on structure floor, 16-27 cm bgs	1280±60	A.D. 650-885	A.D. 675-800	A.D. 738

* All dated material is charcoal.

** Multiple curve intercepts are averaged.



Science, the Public, Management, and the GSENM

Designating the archaeology of the GSENM as one of the values worthy of "scientific study and protection" is a strong statement of the importance of archaeology of this region. The work presented by the several scholars at this conference and earlier work by McFadden, Geib, Tipps, Lister and Ambler, Steward, and others has demonstrated the richness of the cultural heritage here. Even the modest tests that we carried out at the Lampstand Ruins buttress the argument that the research potential of the new Monument is great. How can the Monument serve science? The public? And what are the implications of such directions for managers? We offer a few comments on each of these topics.

Science (Archaeology)

We presume that knowing the human history of the Monument is a goal that will be actively pursued. With that presumption in mind, we suggest some general directions to encourage productive science/archaeology.

Native American Involvement

Archaeology in the post-NAGPRA (Native American Grave Protection and Repatriation Act) world must consider and respect the interests and concerns of native peoples if archaeological research is focused on their history. A recently completed project at Fish Lake that was a partnership between local native people and archaeologists provides one example of the rewards of such arrangements.

Regional Perspectives

Broad views in archaeology are most rewarding and are best achieved through longitudinal studies. Current work in Capitol Reef is beginning to pay dividends after two field seasons. The tests at the Lampstand Ruins and the tests planned at a Fremont structural site (also

outside the Park boundaries) add to the broader view.

Research on Existing Collections

Much can be learned from new approaches to existing collections. In the Monument, there are wonderful collections from Coombs Village available for research. Private collections should not be ignored. Initiation of dialogues with local collectors and examination of the material they hold can help identify the range of time periods represented and perhaps important sites.

Collaborative Projects

Multidisciplinary efforts are likewise rewarding. Archaeologists should look to specialists in the natural sciences as we try to understand the cultural ecology of regions. Paleoenvironmental reconstruction is one goal of the pack rat studies we are doing with Jim Mead and his students from Northern Arizona University in Capitol Reef.

We believe that no specific research agenda needs to be set for archaeologists. The range of potential topics is great, and that range will only expand as more becomes known of the regional history. For many of the researchers involved in this symposium, the archaeology of the area is particularly intriguing because it is an Anasazi-Fremont frontier, and offers much in the way of research potential. Certainly that interest is driving our Lampstand work as well as the upcoming excavations at a Fremont structural site. Other topics and other cultural periods are just as intriguing. Very little is known of either Archaic or post-farming hunter-gatherer patterns and historic archaeology on both European and Native sites seems a fruitful endeavor.

The Public

All public programs are educational in orientation. Educational opportunities can take at least two forms: hands-on or passive. The latter is exemplified by static museum exhibits, road signs, etc., while participation in excavation projects is a common example of



the former. Public experience need not be dichotomized, however. Many museum experiences now include some hands-on exhibits (corn grinding, handling artifacts, for example). Interpretive trails through regions where sites occur are popular and excellent approaches to a more involved educational experience. More involvement can translate into more public support.

Management

Preservation is a tricky issue faced by archaeologists and managers everywhere, given that archaeological resources are finite and, unlike an endangered plant, cannot be nurtured back into greater abundance. Site preservation and management, in most cases, mean leaving the resources alone. However, if you designate it (the Monument), they (the public) will come. From a manager's perspective, it would be much better to be proactive; whether or not they do come, planning has to be done in anticipation that they will. Our Capitol Reef work is unavoidably many years "after the fact" of Park creation, which exemplifies a fundamental preservation quandary: it is difficult to protect and preserve resources when we don't know what or where they are. This is an obvious challenge for the GSENM, especially considering the remoteness and ruggedness of the region. Certainly some portions of the Monument have been touched upon in past inventories, and a Class I study summarizing that work is a good first step. However, such a summary cannot replace a systematic inventory. Preservation must be preceded by documentation.

Conclusions

Learning from the land requires an effort, and we believe that this symposium is a good indication of the desires of the GSENM Management Planning Team to begin that effort. Our work at Lampstand and in CRNP has convinced us that the effort is worthwhile, and we may yet achieve a more holistic view of regional prehistory if the archaeology is

protected. Learning from the land means nothing more, and nothing less, than to preserve its cultural and other resources so that they indeed can teach us.

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A Dietary Reconstruction for the Virgin River Branch Anasazi

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ABSTRACT

■ Many have argued that the Virgin River Branch Anasazi practiced a mixed subsistence economy during their initial phase of occupation [Basketmaker II-III (A.D. 1-700)], followed by periods of agricultural intensification and resource diversification during the later phase of occupation [Pueblo I-II (A.D. 700-1250)]. The results of the study presented here, in which multiple lines of evidence from floral, faunal, and stable isotope analyses are used to reconstruct the diet, argue convincingly that the Virgin River Branch Anasazi were full-time agriculturalists whose diet changed little through time. Maize was the dietary staple and was consumed, at times, in large amounts. This overreliance on maize, presumably during periods of adverse climate, resulted in times of nutritional and social stress. The results call into question the traditional view of subsistence and suggest future avenues of research.

The Virgin River Branch Anasazi (henceforth referred to as the Virgin Anasazi) are an archaeologically defined prehistoric culture that occupied the western margin of the Colorado Plateau north of the Grand Canyon, Arizona and south of the Virgin River drainage in southwestern Utah. As far east as the Paria River, Virgin Anasazi territories are found over nearly 40 percent of the Grand Staircase-Escalante National Monument. To the west, the Virgin Anasazi are found in the Basin and Range of southern Nevada. Radiocarbon and dendrochronological dates indicate that many preceramic Virgin Anasazi sites are Basketmaker II (A.D. 1-400) (Douglas McFadden, 1996, pers. comm.). Many sites were abandoned around A.D. 1150 and the region was largely depopulated after A.D. 1250 (Allison, 1996).

The environment within which the Virgin Anasazi lived is marked by cold winters, short growing seasons, hot summers, sparse precipitation, poor soils, and a high degree of climatic variability. The Virgin Anasazi, for at least 1,300 years, successfully adapted to and developed within this harsh environment. The key to understanding this success, and why it did not

last, is to be found in their subsistence practices. Surprisingly, after nearly four decades of research, the composition of the Virgin Anasazi diet and how it changed through time are still subjects of debate. At the center of this debate is the importance of agricultural products, namely maize, in the diet.

Early researchers held that during the initial phase of Virgin Anasazi occupation [Basketmaker II-III (A.D. 1-700)], agriculture was a full-time pursuit (e.g., Aikens, 1965, 1966; Fowler and Aikens, 1963; Shutler, 1961) with wild plant and animal utilization decreasing only slightly during the later phase of occupation [Pueblo I-II (A.D. 700-1250)] (Aikens, 1965, 1966). This view is held by a minority today (Dalley and McFadden, 1985, 1988). Most explanations of Virgin Anasazi subsistence proffered today argued that the Basketmaker peoples were essentially hunter-gatherers who supplemented their diet with maize and that a mixed subsistence economy was pursued throughout occupation (Heath, 1986, 1988b; Janetski and Hall, 1983; Lyneis,



1992; Moffit and Chang, 1978; Moffit et al., 1978; Nickens and Kvamme, 1981; Valdez, 1993; Westfall, 1987; Westfall et al., 1987). Agricultural intensification during later Puebloan times is argued by a few (Larson, 1996; Larson and Michaelson, 1990; Larson et al., 1996). Some argue that this intensification was also accompanied by a diversification in the subsistence base (increase in the number of wildtype taxa utilized) in the northern southwest during later Puebloan times (e.g., Benz, 1984; Doebley, 1981; Gasser, 1982; Stiger, 1977; Fry and Hall, 1975). Thus, the dominant view today assumes a gradual shift from hunting and gathering to agriculture, a continued increase in the importance of agricultural products from Basketmaker through Pueblo times, and a diversification in the wildtypes utilized prior to abandonment.

Recent evidence from Cedar Mesa, Utah (Matson and Chisholm, 1991; Chisholm and Matson, 1994), Mesa Verde, Colorado (Decker and Tieszen, 1989), and the Four Corners region in general (Minnis, 1989) indicates a substantial reliance on maize agriculture from the beginning of Basketmaker II times. These studies also show that maize remained an important and constant component in the Anasazi diet into and throughout Pueblo times. In fact, the variation between Basketmaker and Pueblo populations in the amounts of maize consumed appears to be relatively small. This lack of intensification may also have been accompanied by a lack of resource diversification. Leonard (1989) has shown that once the results of most studies arguing for an increase in the number of wildtypes utilized prior to abandonment are corrected for sample size effects, diversification is lacking.

Most dietary reconstructions for the Virgin Anasazi, and the Western Anasazi in general, have focused on indirect and limited data sets which are rarely integrated. Here, I will present the results of a dietary reconstruction for the Virgin Anasazi that integrates the floral, faunal, stable carbon isotope, bioarchaeological, and settlement evidence. Although this study focuses on the Virgin Anasazi, reference to

other Western Anasazi groups is frequent, as I believe the data indicate a general continuity, especially concerning subsistence, among all Western Anasazi groups.

Floral Analysis

Paleoethnobotanists practicing in the American southwest have primarily used flotation data to reconstruct the floral aspects of prehistoric subsistence strategies. Macrobotanicals are those carbonized or desiccated plant parts that can be identified under low-power magnification. Analyses in the Virgin Anasazi area have been conducted exclusively on soil samples that have undergone water flotation. Although this is an important and valuable technique in the investigation of prehistoric food consumption, it is an indirect and incomplete measure, with any attempt at the quantification of dietary constituents being confounded by the complex processes of differential deposition, preservation, and recovery.

Thirty-three Virgin Anasazi sites have undergone such analysis with soil samples being collected from a variety of contexts (Allison, 1990; Heath 1986, 1987, 1988a,b, 1992; Jacklin, 1988; Martin, 1996a,b; Newman, 1988, 1990, 1992b; Scott, 1985; Valdez, 1993; Van Ness, 1987). Insufficient and biased recovery, as well as incomplete and inaccurate reporting of results, has confounded previous macrobotanical analyses for the Virgin Anasazi. In spite of the shortcomings inherent in the database, a number of convincing patterns still emerge.

Table 1 lists the ubiquity values for the identifiable taxa recovered from all flotation samples. Ubiquity values are simply a measure of the number of samples in which the taxon appears within a group of samples. Samples are grouped here by the time periods used by most archaeologists practicing in the Virgin Anasazi culture area [with Basketmaker II (A.D. 1-400) and Basketmaker III (A.D. 400-700) being combined due to imprecise dating



Table 1. Ubiquity (percentage present) values^a for identifiable taxa recovered from the flotation samples.

Taxa	BM	P I	EP II	LP II
SEEDS:				
<i>Amaranthus</i> sp.	5.1	3.6	4.0	11.7
<i>Arctostaphylos</i> sp.		3.6		
<i>Chenopodium</i> spp.	10.3	16.1	34.7	24.5
<i>Corispermum</i> sp.	7.7			
<i>Caryophanta vivipara</i>	5.1			
<i>Cucurbita</i> sp.		3.6		
<i>Descurainia</i> sp.	5.1	10.7		7.4
<i>Echinocereus</i> sp.				3.2
<i>Helianthus</i> sp.		3.6	4.0	4.3
<i>Hypericum</i> sp.	17.9			5.3
<i>Lepidium</i> sp.		3.6		
<i>Mentzelia</i> sp.	5.1			12.8
<i>Oryzopsis hymenoides</i>	5.1			6.4
<i>Phaseolus vulgaris</i>				6.4
<i>Physalis</i> sp.			4.0	
<i>Portulaca</i> sp.	25.6	3.6	5.3	14.9
<i>Potentilla</i> sp.			4.0	
<i>Sphaeralcea</i> sp.		3.6		9.6
<i>Typha</i> sp.				4.3
<i>Yucca baccata</i>				3.2
<i>Zea mays</i>	20.5	23.2	17.3	34.0
FAMILIES:				
Asteraceae				6.4
Brassicaceae	12.8			9.6
Caryophyllaceae			4.0	
Cheno-Ams	41.0	25.0	9.3	51.1
Cyperaceae	5.1			
Malvaceae				5.3
Onagraceae			4.0	
Poaceae	10.3	8.9	4.0	13.8
PLANT PARTS:				
<i>Zea mays</i> cob fragments	33.3	41.1	46.7	39.4
<i>Pinus</i> sp. nutshell	7.7	16.1		19.1
Number of Taxa	11	11	7	15
Number of Sites	3	8	11	11
Number of Samples	39	56	75	94
Total Soil Volume (l)	39.0	57.5	75.0	218.5

^a Only ubiquity values $\geq 3\%$ are given.

NOTE: BM=Basketmaker (A.D. 1-700), P I=Pueblo I (A.D. 700-900), EP II=Early Pueblo II (A.D. 900-1050), LP II=Late Pueblo II (A.D. 1050-1250).

and small sample size]. By only considering ubiquities greater than 3 percent, rare taxa are removed from the analysis. There are a number of important points to be gleaned from this table. First, a rather limited set of wild plants were used in appreciable amounts. This is expected since the marginal environment within which the Virgin Anasazi lived resulted in the irregular, unpredictable, and sparse

distribution of edible wild plants. Second, most of these plants (e.g., *Amaranthus* sp., *Chenopodium* spp., *Portulaca* sp., *Descurainia* sp., *Mentzelia* sp., *Helianthus* sp.) are weedy annuals that thrive in disturbed soils. Many of these plants would have been found around and within agricultural fields, in and around habitation sites, and over midden areas. Ethnographic evidence indicates that the growth of such plants was encouraged through selective weeding (Dobyns, 1979; Ford, 1984; Minnis, 1978). Third, maize (*Zea mays*) was of considerable importance. Both cob fragments and kernels display consistently high ubiquity values. Only *Chenopodium* spp. and *Portulaca* sp. are more ubiquitous than maize kernels. Fourth, even though the sample sizes increase through time, the number of taxa utilized does not. The slight increase during the Late Pueblo II time period is due to sample size effects, as the correlation between sample size and the number of taxa per sample is significant ($r=0.87$, $p<0.001$). Therefore, there is no unequivocal evidence for a diversification in the Virgin Anasazi resource base prior to abandonment.

Pollen data have been used largely in vegetation and climate reconstructions in the American southwest, and their use in dietary reconstructions is of a limited nature. Comparing modern surface samples with those recovered from archaeological contexts, the Cheno-ams and Poaceae are found in greater percentages (not necessarily greater ubiquity) than in modern samples (e.g., Lindsay, 1986; Newman, 1992a; Scott, 1981, 1985). Most taxa in these families are weedy annuals apt to invade disturbed soils. Maize is the only domesticated recovered in notable amounts. The pollen studies also suggest the cultural use and consumption of *Cleome* sp., *Typha* sp., and various cacti.



The results of flotation and pollen studies for other Western Anasazi groups are in concordance with the data presented here (e.g. Aasen, 1984; Benz, 1984; Gasser, 1982; Heath and Schroedl, 1989; Lepofsky, 1986; Miksicek, 1978; Minnis and Ford, 1977). Few new taxa are reported and ubiquity values are very similar. This attests to the general uniformity in the floral component of the diet over Western Anasazi territories.

A more direct source of information on diet is found in the analysis of coprolites or desiccated human feces. Unfortunately, no such studies have been conducted for the Virgin Anasazi. However, studies have been conducted on coprolites collected from a number of Western Anasazi sites (e.g., Aasen, 1984; Cummings, 1994; Fry, 1977; Fry and Hall, 1975, 1986; Minnis, 1989; Stiger, 1977, 1979; Scott, 1979; Williams-Dean, 1986). The macroplant data from a select number of these studies is summarized in Table 2, with every effort being made to accurately place the sites within the chronological scheme used here. We see a great deal of congruence between the Virgin Anasazi flotation and Western Anasazi coprolite data sets. Additionally, pollen studies conducted on these coprolites (Aasen, 1984; Scott, 1979; Williams-Dean, 1986) indicate the importance of the same wild plants, as well as squash and beans, which are usually underrepresented in flotation samples. Maize

Table 2. Ubiquity (percentage presence) values for macroplant remains recovered from Western Anasazi coprolites.

Taxa ^a	BM II	BM III	P I	EP II	LP II
<i>Allium</i> sp. (epidermis)					1.2
<i>Amaranthus</i> sp.	2.9	5.0		10.5	14.0
<i>Artemisia</i> sp.		5.0			<1.0
Asteraceae					4.8
<i>Atriplex</i> sp. (leaf)					7.0
Cactaceae				36.8	<1.0
(epidermis & spine)					
<i>Caltis reticulata</i>					2.3
Cheno-Ams	2.9				
Chenopodiaceae (leaf)	20.6				
<i>Chenopodium</i> sp.	2.9	25.0		15.8	16.4
<i>Cleome</i> sp.	8.8	10.0		21.1	7.6
<i>Carispermum</i> sp.				5.3	
<i>Cucurbita</i> sp. (seed & tissue)	17.6	40.0	100	63.2	26.3
<i>Elymus</i> sp.					<1.0
<i>Gossypium hirsutum</i>	5.9			5.3	12.9
<i>Helianthus</i> sp.				5.3	2.9
<i>Lepidium</i> sp.	2.9				2.9
<i>Opuntia</i> sp.	20.6	40.0		31.6	24.6
<i>Oryzopsis hymenoides</i>	11.8	5.0			6.4
<i>Panicum</i> sp.				5.3	
<i>Phaseolus vulgaris</i> (epidermis)		5.0		5.3	7.0
<i>Physalis</i> sp.		20.0		42.1	14.0
<i>Pinus</i> sp. (nutshell)	32.4	35.0		59.9	15.2
Paaceae	8.8	5.0			8.2
<i>Portulaca</i> sp.	2.9	25.0	100	52.6	12.3
<i>Prunus virginiana</i>		5.0			1.8
<i>Rhus trilobata</i>					5.3
<i>Shepherdia</i> sp.					1.8
<i>Sporobolus</i> sp.					1.8
<i>Vitis arizonica</i>				5.3	<1.0
<i>Yucca</i> sp. (seed & pod)				5.3	
<i>Zea mays</i> (seed & tissue)	82.3	65.0	100	94.2	86.5
Total number of samples	34	20	1	19	171

^aTaxa are represented by seeds unless otherwise noted.

Data from Aasen (1984), Fry (1977), Fry and Hall (1986), Stiger (1977).

NOTE: BM II=Basketmaker II (A.D. 1-400), BM III=Basketmaker III (A.D. 400-700), P I=Pueblo I (A.D. 700-900), EP II=Early Pueblo II (A.D. 900-1050), LP II=Late Pueblo II (A.D. 1050-1250).

macroplant remains were recovered from 84.5 percent of the 245 coprolites considered here. Fry and Hall (1986) determined the dry weight percentages of the various constituents recovered from coprolites at Antelope House, Canyon de Chelly. Maize constituted on average between 30 and 50 percent of coprolites within the various time periods (range 0.12-97.6 percent, n=90). Aasen (1984) examined 28 Basketmaker II coprolites from Turkey Pen



Ruin, Cedar Mesa. Maize was recovered from 25 of the 28 coprolites, 17 of which were between 50 and 100 percent maize.

Table 3 lists, in addition to the cultigens, the ubiquity values for the *most* important wild plant food resources as indicated by the evidence assembled here. The results presented above, although not conducive to the quantification of dietary constituents, indicate the importance of cultigens, namely maize. The relatively high absolute counts and ubiquity values for maize in flotation, pollen, and coprolite samples argue for its importance throughout the Virgin Anasazi occupation. Ethnographic evidence indicates that wild plant collection among the Pueblo Indians was small-scale, opportunistic, and scheduled so as not to interfere with agricultural practices (Ford, 1968; Stevenson, 1915; Whiting, 1939). As a result of agricultural disturbances, considerable amounts of edible weedy annuals would have been readily available and seasonal forays to harvest pine nuts or collect wild fruits may have been infrequent.

Table 3. Overall ubiquity (percentage presence) values for the most important taxa recovered from the samples considered in this study.

Food Items	Flotation ^a	Coprolite
Cultivated Plants		
Beans (<i>Phaseolus vulgaris</i>)	2.3(334)	5.7
Maize [<i>Zea mays</i>]	25.0(>15,000)	84.9
Squash (<i>Cucurbita</i> sp.)	1.5(13)	29.4
Wild Plants		
Beeweed (<i>Cleome</i> sp.)	<1.0(2)	9.0
Cactaceae ^b	3.0(57)	26.1
Cheno-Ams	30.7(1923)	<1.0
Goosefoot (<i>Chenopodium</i> spp.)	23.9(1302)	15.1
Ground-Cherry (<i>Physalis</i> sp.)	2.3(10)	13.9
Indian rice grass (<i>Oryzopsis hymenoides</i>)	2.7(8)	6.5
Pigweed (<i>Amaranthus</i> sp.)	7.6(53)	10.6
Pinyon pine (<i>Pinus edulis</i>) ^c	12.1(>253)	22.4
Purslane (<i>Portulaca aleracea</i>)	11.7(349)	15.5
Sunflower (<i>Helianthus</i> sp.)	3.4(1172)	2.4
Yucca (<i>Yucca</i> sp.)	1.1(10)	<1.0
Total number of samples	264	245

^aRaw counts in parentheses.

^bIncludes specimens identified as *Opuntia* spp., *Caryophanta* sp., and *Echinocereus* sp.

^cAs evidenced by nutshell.

Faunal Analysis

Fourteen sites that have had their faunal assemblages described are considered in this study (Aikens, 1965; Allison, 1990; Emslie, 1981; Nauta, 1995; Walling et al., 1986). Excavation techniques not amiable to the recovery of bone and poor preservation are partly responsible for the relatively meager recovery of faunal remains. Although excavation procedures have resulted in reduced recovery, they are not enough to account for the low number of bones coming out of most sites. For example, only three small fragments of bone were recovered from the Pinenut site (AZ:B:6:44) and all fill went through 1/4-inch mesh screens (Westfall, 1987).

Table 4 lists the unmodified faunal remains recovered from the sites considered in this study. Unfortunately, the small number of sites and the uneven coverage prevent any spacio-temporal analysis. Taken as a whole, the importance of artiodactyls and lagomorphs is apparent. Most of the large and small mammals listed as unidentifiable are more than likely found in the two respective categories. Most of the artiodactyls are represented by tarsals, carpals, and phalanges suggesting that butchering occurred at the kill site (Emslie, 1981; Nauta, 1995). Most of the bird remains are turkeys (*Melagris gallopavo*), which were domesticated during Pueblo II times. The only carnivore significantly represented is dog/coyote (*Canis* sp.), which was also domesticated during Pueblo II times. The presence of gnaw marks on some bones (e.g., Nauta, 1995) point to the potential biasing effect dogs may have had on the faunal assemblages presented here. The poor condition of the bone is evidenced by the fact that 73 percent of the recovered bone is either unidentifiable below the level of order or unknown. A majority of elements recovered represent dense bone, which also implies that preservational factors may have affected the assemblages.

Small mammals, including lagomorphs and rodents, are prolific breeders reaching high



Table 4. Unmodified faunal remains recovered from the sites considered in this study.^a

Toxo	Common Name	NISP ^b
Bird (Aves)		
<i>Aphelocoma coerulescens</i>	Scrub jay	1
<i>Grus canadensis</i>	Sandhill crane	1
<i>Lophortyx gambelii</i>	Gambel's quail	1
<i>Melagris gallopavo</i>	Common turkey	24
Columbidae		1
Mammal (Mammalia)		
Artiodactyla		266
<i>Antilocapra americana</i>	Pronghorn antelope	135
<i>Odocoileus hemionus</i>	Mule deer	337
Bovidae		9
<i>Ovis canadensis</i>	Mountain sheep	155
Carnivora		
<i>Canis latrans</i>	Coyote	3
<i>Canis sp.</i>	Dog	63
<i>Felis rufus</i>	Bobcat	11
Lagomorpha		9
Leporidae		359
<i>Lepus californicus</i>	Black-tailed jackrabbit	92
<i>Lepus sp.</i>	Hare	78
<i>Sylvilagus spp.</i>	Rabbit	202
Rodentia		25
<i>Erethizon dorsatum</i>	Porcupine	7
<i>Perognathus spp.</i>	Pocket mouse	5
<i>Dipodomys ordii</i>	Kangaroo rat	4
<i>Neotoma spp.</i>	Pack rat	10
<i>Microtus sp.</i>	Vole	1
Geomyidae		1
<i>Thomomys sp.</i>	Pocket gopher	26
Sciuridae		3
<i>Spermophilus sp.</i>	Squirrel	4
Reptile (Reptilia)		
Iguanidae		1
Unidentifiable:		
Bird:		
Medium		12
Large		28
Mammal:		
Small		214
Medium		478
Large		134
Reptile		1688
		1

^aCounts given for lowest taxonomic level possible.

^bNumber of identified specimens (does not include partial skeletons).

population densities in favorable conditions. Anthropogenic alterations, which created environments for ruderal plants, also created favorable habitats for small mammals (Seme, 1984). Agricultural fields create habitat for lagomorphs and rodents, which have

population densities that vary with field cycles (Seme, 1984). Favorable habitats would also have been created in association with water and soil control devices, refuse areas, and storage facilities. Locally and readily available most of the year, these animals were probably casually collected during daily activities, as well as selectively hunted in drives. Small game capture was the main source of protein for the Southern Paiute (Kelly and Fowler, 1986) and probably for the Virgin Anasazi as well.

Large mammals, on the other hand, would have been an irregular, unreliable, high-energy cost resource for which hunting would have been a time-consuming affair. Given the restrictions of agriculture, the hunting of large game would have been difficult and was probably infrequent and associated with ritual and communal activities; however, the actual caloric contribution of all animals to the diet was probably rather small and on the order of 10 percent of total calories.

Stable Carbon Isotope Analysis

A new technique that actually allows the determination of various dietary constituents is the analysis of stable carbon isotope ratios preserved in the collagen of prehistoric human skeletal remains.

In the process of photosynthesis, plants take in carbon dioxide from the atmosphere and reduce it to carbohydrate. This fixation of CO₂ in terrestrial plants proceeds via one of three possible pathways: C₃, C₄, and crassulacean acid metabolism (CAM). The carbon in atmospheric CO₂ exists as

one of two stable isotopes: 99 percent of which is ¹²C and 1 percent of which is ¹³C. Plants do not assimilate these two stable isotopes in the natural ratio of 99:1 during photosynthesis, but discriminate against the heavier form. This is known as isotopic



fractionation and results in a difference between the ^{13}C content of plant tissue and the atmosphere. The extent of fractionation depends on the photosynthetic pathway a plant employs.

The C_3 plants have a $\delta^{13}\text{C}$ range of -21 to -32‰ with a mean of -26.5‰. The C_4 plants have a $\delta^{13}\text{C}$ range of -9 to -16‰, with a mean of -12.5‰. Note that the two ranges do not overlap and that there is a 14‰ separation between the means. In arid environments, CAM plants' $\delta^{13}\text{C}$ values tend to resemble C_4 plants, whereas in other types of environments they resemble C_3 plants.

Animal studies have conclusively demonstrated that the ^{13}C content of an animal's diet is reflected in its tissue (DeNiro and Epstein, 1978; Schoeninger and DeNiro, 1984; Vogel, 1978; and others). These studies showed little variation in $\delta^{13}\text{C}$ values of the diet and the whole body of the organism. However, fractionation of the carbon does occur during the formation of various tissues (DeNiro and Epstein, 1978; Vogel 1978). Collagen has a fractionation factor of approximately 4.5‰ (i.e., collagen values are 4.5‰ more positive than the diet). Animal studies have also demonstrated that individuals within a population fed the same diets have isotopic ratios that do not differ significantly from one another (± 1 ‰), show no age or sex differences, and are the same for all bones within a single individual (Bumsted, 1983, 1984; DeNiro and Schoeninger, 1983; and others). All values given here were made on bone collagen, which has a turnover rate of 10 to 30 years and thereby represents long-term dietary uptake.

Table 5 presents the $\delta^{13}\text{C}$ values for those plants and animals that were determined above to be the most important food resources. The mean $\delta^{13}\text{C}$ value for the C_4/CAM plants is

Table 5. Stable carbon isotope ratio values for the most important food items used by the Virgin Anosozí.

Food Items	$\delta^{13}\text{C}$ ‰ (PDB)
Cultivated Plants	
Maize (<i>Zea mays</i>)	-10.0
Beans (<i>Phaseolus vulgaris</i>)	-23.3
Squash (<i>Cucurbita</i> sp.)	-24.7
Wild Plants	
Pigweed (<i>Amaranthus</i> sp.)	-9.8
Goosefoot (<i>Chenopodium</i> sp.)	-24.0
Sunflower (<i>Helianthus</i> sp.)	-26.3
Prickly pear (<i>Opuntia</i> spp.)	-12.5
Indian rice grass (<i>Oryzopsis hymenoides</i>)	-22.3
Pinyon pine (<i>Pinus edulis</i>)	-28.5
Purslane (<i>Portulaca oleracea</i>)	-10.6
Yucca (<i>Yucca</i> sp.)	-15.7
Beeweed (<i>Cleome</i> sp.)	-22.8
Ground-Cherry (<i>Physalis</i> sp.)	-25.7
Fauna	
Mule deer (<i>Odocoileus hemionus</i>)	-21.4
Mountain sheep (<i>Ovis canadensis</i>)	-19.0
Pronghorn (<i>Antilocapra americana</i>)	-22.2
Hare (<i>Lepus</i> sp.)	-20.4
Rabbit (<i>Sylvilagus</i> sp.)	-22.6
Turkey (<i>Meleagris gallopavo</i>)	-18.3

-10.7‰ and the mean $\delta^{13}\text{C}$ value for the C_3 plants is -24.7‰. Maize is the only C_4 domesticate, and few wild plants are C_4/CAM . The mean $\delta^{13}\text{C}$ value for meat is -20.7‰ and, as such, it can be considered in the C_3 plant category.

Seventeen individuals from eight sites representing all time periods were collected from within the study area and underwent stable carbon isotope ratio analysis. The results are presented in Table 6. As shown, there is little temporal variation, and the C_4/CAM plant input is large.

Based on determinations made of the important plant and animals presented in Table 5, the mean $\delta^{13}\text{C}$ value for the C_4/CAM plants is -10.7‰. This is essentially identical to the $\delta^{13}\text{C}$

¹ Because the difference in stable isotopes is very small, the absolute abundance of each is not determined. Instead, the isotopic content of a plant is measured as a ratio of the stable isotopes ($^{13}\text{C}/^{12}\text{C}$) relative to a standard, expressed in what is known as delta (δ) notation, and measured in parts per thousand or per mil (‰):

$$\delta^{13}\text{C}\text{‰} = \left[\left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{sample}} / \left(\frac{^{13}\text{C}}{^{12}\text{C}} \right)_{\text{standard}} - 1 \right] 10^3$$

The standard is the Pee Dee belemnite (PDB) carbonote.



Table 6. The stable carbon isotope ratio results for the Virgin Anasazi.

Site	Time Period	$\delta^{13}\text{C}$ (‰, PDB)	Estimated % C_4/CAM (± 10)
42Ka2548	Basketmaker II	-8.2	86
	Basketmaker II	-7.8	89
	Basketmaker II	-7.8	89
42Ka3576	Basketmaker II	-8.0	87
	Mean and s.d.	-8.0 \pm 0.2	
42Ka3575	Basketmaker III	-7.9	88
	Basketmaker III	-12.0	60
	Mean and s.d.	-10.0 \pm 2.9	
42Ws956	Pueblo I	-8.3	85
42Ws957	Pueblo I	-10.2	71
	Mean and s.d.	-9.3 \pm 1.4	
42Ws953	Early Pueblo II	-8.5	84
42Ws957	Early Pueblo II	-9.3	78
42Ws964	Early Pueblo II	-8.8	81
	Early Pueblo II	-9.3	85
	Early Pueblo II	-7.0	94
	Early Pueblo II	-9.5	76
	Mean and s.d.	-8.6 \pm 0.9	
42Ka3976	Late Pueblo II	-7.5	91
	Late Pueblo II	-8.4	84
	Late Pueblo II	-6.5	98
	Mean and s.d.	-7.5 \pm 1.0	

value for maize (-10.0‰) and not far from the category $\delta^{13}\text{C}$ value given above (-12.5‰). The mean $\delta^{13}\text{C}$ value for the C_3 plants is -24.7‰. This is close to the goosefoot $\delta^{13}\text{C}$ value of -24.0‰ and not far from the category $\delta^{13}\text{C}$ value given above (-26.5‰). Assuming a collagen fractionation factor of 4.5 for carbon, the percentage of C_4/CAM plants in the diet (that is, collagen-derived protein) ranges from 60 to 98 percent. This is, of course, a proportional estimate of C_4/CAM plants based on pathway averages and a strictly vegetarian diet. However, the mean $\delta^{13}\text{C}$ value for meat is -20.7‰ and is on the positive end of the C_3 category. As such, it can be considered in the C_3 plant category. Overall, the carbon isotope data shows little variation and a lack of spacio-temporal patterning.

The results presented here are consistent with those from other isotope studies for the Western Anasazi (Chisholm and Matson,

1994; Decker and Tieszen, 1989; Martin et al., 1991), again attesting to the general uniformity in the diet over Western Anasazi territories. The stable isotope data corroborate the results outlined thus far and indicate that the Virgin Anasazi relied heavily on cultigens and consumed low levels of meat and wild plants. The diet changed little through time, with maize being a dietary staple from the start of Basketmaker times. The extent of maize consumption seems to be greater than has previously been estimated and is on the order of 75 \pm 10 percent of total calories. Claims that wild C_4/CAM plants composed more than 10 percent of the diet seem unfounded.

Based on the flotation, pollen, coprolite, faunal, and bone chemistry results, the diet of the Virgin Anasazi can be reconstructed with a fair degree of accuracy. Since there is little evidence for temporal or spatial change in the diet, what follows is for the entire study area throughout the occupation. It was found that agricultural products, namely maize, comprised the bulk of the calories. Most preliteracy agricultural societies derive 70-80 percent of their calories from starchy staples and this is not an unrealistic estimate (Gaulin and Konner, 1977). The lack of significant change in the isotopic content of the diet, even with the introduction of beans and the possible domestication of turkeys and dogs in Puebloan times, highlights the importance of maize. The results of the stable isotope and faunal analyses indicate that meat made up about 10 percent of the diet; half (on an annual basis) of which would have come from artiodactyls and half from lagomorphs and rodents. The floral analyses indicate that wild plant collection focused on the many weedy annuals that were made readily available as the result of agricultural disturbances. Seasonal forays to harvest pine nuts or collect wild fruits may have been infrequent, but important in terms of nutrients.



Paleonutrition and Paleopathology

Even given the high degree of spacio-temporal stability in the diet of the Virgin Anasazi, it is impossible to determine the composition of the diet at any point in time with enough accuracy to be able to evaluate whether nutritional needs would have been met. Assuming adequate calories, nutrient requirements would have been met by the cultigens alone with any deficiencies in vitamins and minerals (namely iron) being found in wild plants (esp. greens). However, bad years would have resulted in a heavy reliance on stored foods. This would have meant close to 100 percent consumption of maize for extended periods of time. Maize is a poor source of protein, low in the essential amino acids lysine and tryptophan, and low in iron, with only 2.7mg/100g. Some clues as to the nutritional adequacy of the Western Anasazi diet can be found in the paleopathological data.

Skeletal indicators of physiological disruptions resulting from nutritional inadequacies have been noted in bioarchaeological studies of human remains from the American southwest. Cranial lesions descriptively known as porotic hyperostosis are ubiquitous among prehistoric southwestern populations, particularly the Western Anasazi (El-Najjar, 1976; El-Najjar et al., 1976; Martin et al., 1991; Ferguson, 1980; and others).

Anemia causes the marrow cavity in cancellous bone to expand into the normally smooth cortical bone, resulting in the porous appearance of these lesions. Iron deficiency anemia has been linked to an overdependence on maize (e.g., El-Najjar et al., 1976). Southwestern varieties of maize are low in iron, and what little is present is of low (1 to 7 percent) bioavailability (Bothwell and Charlton, 1981; El-Najjar and Robertson, 1976). Maize also contains phytic acid, which inhibits intestinal absorption of iron (Davidson and Passmore, 1966). Calcium also inhibits the absorption of iron, and many southwestern

Indians often treat maize in alkali solution, thereby increasing its calcium content (e.g., Greenhouse, 1981). Pinyon pine nuts, another important food source of the Western Anasazi, may also have inhibited iron absorption (McFarlane et al., 1988). Human milk is low in iron (circa 0.3 mg/L) and high in calcium and infants nursed longer than 6 months often become anemic. Among the Pueblo Indians, maize and beans are typically used as weaning foods, but meat is not (Corbett, 1968).

There is some debate as to whether this iron deficiency anemia is solely the result of diet or whether other factors, such as sedentism and aggregation, led to the anemia (El-Najjar et al., 1976; Kent, 1986; Walker, 1985). Dense settlements, such as those found in cliff dwellings, manifest poor sanitary conditions, thereby increasing contact with the vectors of infectious disease. The transmission of diarrheal and parasitic infections (Armelagos and Dewey, 1978; Kunitz, 1970) would have led to iron deficiency anemia through blood and iron loss. Although the adverse effects of aggregated populations on health surely exacerbated iron deficiency anemia, the fact that Basketmaker II/III populations exhibit porotic hyperostosis (at possibly the same levels as Pueblo populations) argues for a larger dietary role. Diet is obviously not the only cause of anemia, particularly when diarrheal and parasitic infections lead to gastrointestinal bleeding. However, dietary intake is the most frequent determinant of iron status and is probably the key factor in the etiology of Western Anasazi anemia.

No large-scale bioarchaeological studies have been conducted for the Virgin Anasazi, although similar pathological conditions have been reported. For example, porotic hyperostosis has been reported for an infant from the Late Pueblo II Arroyo site (42Ka3976) (Edgar, 1995).

Settlement Patterns

Settlement data, which is greatly influenced by subsistence strategies, can also inform us as to the nature of the Virgin Anasazi diet. A



rather large inventory of over 1,000 Virgin Anasazi sites has been recorded by the Bureau of Land Management and comprises the database used here (McFadden, 1993). Three distinct areas have undergone survey: 32 km² of the Grand Staircase east of Kanab, 23 km² along the upper Virgin River east of Zion National Park, and 105 km² on the Kolob and Skutumpah terraces below the Pink Cliffs. Intensive surveys within the Grand Staircase tracts have yielded 459 sites at a density of 96/km². Of those sites recorded, 81 percent are architectural (that is, permanent habitations) and represent Basketmaker through Late Pueblo II occupations. Site distributions indicate a steady population increase through time with a noticeable decline in the number of Pueblo I sites. The Virgin River inventories have yielded 202 sites at a density of 60/km². Again, 81 percent were architectural. Interestingly, the site distributions are the converse of those found on the Grand Staircase section with a relatively large number of Pueblo I sites followed by a rapid decline beginning in Early Pueblo II times and virtual abandonment of the area by A.D. 1100. The Kolob and Skutumpah inventories recorded 416 sites, only one of which was architectural; the rest were limited activity sites associated with Archaic, Southern Paiute, and Anasazi hunting and gathering activities. The lack of Virgin Anasazi architectural sites is not surprising given that the growing season is less than 120 days (that needed for maize agriculture) at elevations above 2000 m in the study area.

In the Basin and Range, 98 percent of the recorded sites are found along the perennially spring- and snow-fed Virgin and Muddy Rivers (Lyneis, 1992). The growing season in this portion of the Basin and Range is long enough to allow two crops per year. However, precipitation is insufficient for dry farming and irrigation is absolutely necessary, explaining site placement.

All architectural sites were found near arable land at elevations below 2000 m (>120 frost-free days) and above 1500 m where annual precipitation >230 mm as is required for dry

farming. The data indicate that agriculture was the prime factor in determining site location. The relatively small number of Virgin Anasazi limited activity sites appears to support the assertion that hunting and gathering activities were of little importance. The internal development of sites indicates multiple short-term occupations with the accretional development of storage roomblocks and sequential occupation of sites possessing multiple roomblocks. Many sites appear to have experienced a number of occupational episodes, some with long intervals of abandonment as evidenced by the vertical superpositioning of storage roomblocks and other features.

In summary, the paleopathological and settlement data are in agreement with the conclusions reached above: the Virgin Anasazi were full-time agriculturalists throughout their occupation of the region. This subsistence strategy, practiced in an extremely marginal environment, adversely affected their health and restricted where they could live. Although sedentary, the Virgin Anasazi appeared to have remained highly mobile. As local environments deteriorated, the Virgin Anasazi would have had no choice but to move to more favorable or unaffected areas within the region.

Conclusions

The results of this study convincingly argue a number of salient points: 1) the Virgin Anasazi Basketmaker were agriculturalists, 2) the overall diet changed little through time with no evidence for agricultural intensification or diversification in the resource base in either cultigens or wild resources, 3) those wild plants and animals that were exploited in great numbers were those that would have been associated with agricultural practices, 4) maize was the dietary staple and was consumed, at times, in large amounts, 5) the overreliance on maize, presumably during periods of adverse climate, resulted in times of nutritional stress, and 6) the Virgin Anasazi, although increasing their numbers through time and constructing permanent settlements, remained highly mobile.



The results of this study call into question the traditional view of Virgin Anasazi subsistence and suggest a number of avenues for future research. The Grand Staircase-Escalante National Monument offers an excellent opportunity to address many of the issues raised here, as well as to preserve the archaeological record for future generations of scholars.

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Formative Settlement on the Grand Staircase-Escalante National Monument: A Tale of Two Adaptations

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ABSTRACT

The diverse natural environmental settings found on the Monument are matched by the variety of archeological site types that are found in these settings. My consuming interest over the past 20 years has been to organize these sites in some meaningful fashion. This paper reviews the temporal and spatial distribution of over 1,000 Formative period sites and describes their settlement patterns; that is, how various site types are distributed across the landscape, and how they relate to one another and to significant environmental variables. An understanding of these site-to-site and site-environment relationships will allow for appropriate planning measures to protect them.

A second, more ambitious goal is to offer an interpretation of the two primary settlements, the Virgin Anasazi and the San Rafael Fremont, as being reflections of specialized

■ The Monument contains portions of three distinct physiographic areas that hold significant Formative period (A.D. 1-1300) occupations. Based on recent dating efforts and the inventory of over 1,000 sites, this paper reviews the settlement patterns in each area. On the Grand Staircase, the indigenous Virgin Anasazi depended heavily upon agriculture. The Virgin pattern of settlement seems to reflect a strategy of residential mobility that allowed them to shift among various arable settings, on an annual basis, as conditions changed. This adaptation appears to have restricted architectural site locations to elevations between 5,000 and 7,000 feet—the prehistoric agricultural zone for dryfarming. In the Escalante River drainage, the Fremont were contemporary with the Virgin Anasazi, but their adaptation involved a mix of hunting, gathering, and agriculture that resulted in a highly variable and more dispersed pattern of settlement. It is proposed that the Fremont adaptation involved seasonal movement between farming locations in the perennially watered canyons and winter residential sites in the uplands suitable for big game hunting. The Kaiparowits Plateau was initially occupied by the Fremont and later settled by a group of Anasazi generally thought to have immigrated from the Kayenta area—the nature of the two groups interactions, if any, remains a subject of debate. This paper suggests that both future research investigations, as well as management-oriented inventories in the three areas, would benefit from an approach that focuses on these settlement patterns as reflections of special adaptations to their unique social and environmental settings.

adaptations to the unique environmental settings found in the Monument. The concept of adaptation (O'Brien and Holland, 1992), and of behaviors that are shaped by specific adaptive strategies (McFadden, 1996), provides a useful approach for distinguishing these groups as discrete archeological entities.

Long after the indigenous Virgin and Fremont groups were established, the Kayenta Anasazi are believed to have migrated into the area



(Fowler and Aikens, 1963). The relationship between the Kayenta migrants and the indigenous Fremont and Virgin populations is a subject of continuing debate (Madsen, 1997; Geib, 1996; Euler, 1994). I suggest that focusing on the adaptive behavior of these groups—as reflected in settlement patterning—rather than relying solely on culture trait lists, would be the most effective approach for understanding those relationships.

The Virgin Anasazi

The Virgin Anasazi culture area lies north and west of the Colorado River. The area extends from the hot desert of the lower Virgin River drainage in Nevada into the St. George Basin of Utah and onto the high plateaus of the Arizona Strip and the Grand Staircase portion of Utah (Figure 1). The Monument encompasses the eastern third of the Grand Staircase physiographic section (Stokes, 1986) and holds a significant number of Virgin Anasazi sites.

The Agricultural Zone

The relevance of the Grand Staircase to Formative settlement studies is its physical

structure; rising from about 5,000 feet (1524 m) on the south through a series of successively higher cliffs and terraces to 9,000 feet (2743 m) at Bryce Canyon, its elevational extremes bracket the potential agricultural zone. Since arable soils can be found at all levels of the Grand Staircase, it is the elevation-dependent variables of precipitation and length of growing season that determine agricultural site locations on this part of the Monument. Virtually all recorded architectural sites on the Grand Staircase are located between 5,000 and 7,000 feet (1524–2134 m) where annual precipitation is over 10 inches (25 cm) and the growing season exceeds 120 days. In addition to informing us about Virgin subsistence practices, these parameters allow us to predict site locations with some degree of accuracy.

The Grand Staircase Inventory Data

The majority of archeological data for the Grand Staircase is derived from three intuitively based inventories: the Seaman Wash Inventory, Fin Little Inventory, and a reconnaissance in the Kitchen Corral drainage (McFadden, 1996) (Figure 2). These in-house investigations have identified nearly 600 sites; over 80 percent of

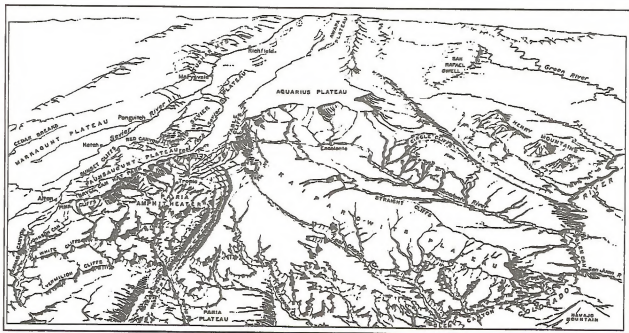


Figure 1. Topographic sketch of the Grand Staircase-Escalante National Monument setting (after Gregory and Moore, 1931).

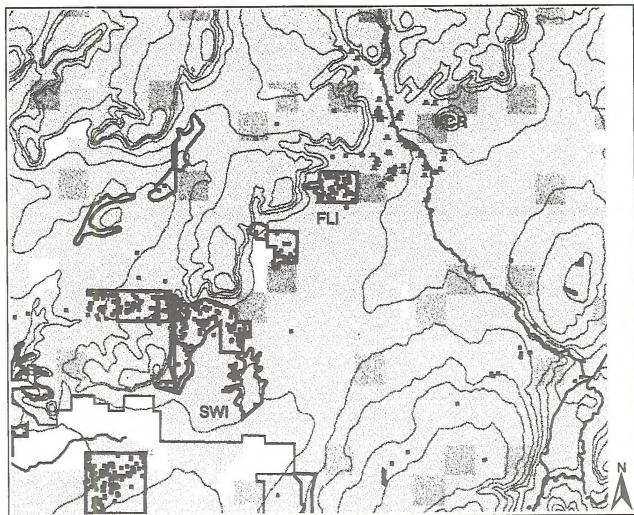


Figure 2. Grand Staircase inventory units: Fin Little (FLI), Seaman Wash (SWI), and Kitchen Carral reconnaissance (KCR).

the sites are architectural, and most display evidence for both residential and storage structures. Architectural styles and ceramic types indicate that the entire Anasazi sequence is represented. Site densities are high, even by southwest standards, averaging about 40 per square mile.

Although the inventories did not statistically sample the area, they did examine a broad range of arable settings suitable for runoff or dryfarming techniques. The settings were characterized by several different landforms with variable aspects ranging from north to south, located at elevations between 5,000 and 6,400 feet (1524 and 1950 m). Vegetative cover varied from dense pinyon-juniper to open big sage. Soil types were diverse with different degrees of water retention capability.

Virtually all of these microenvironments were found to contain structural sites. A particularly significant finding was that most of these settings displayed sites from more than one, and sometimes all, periods of occupation—this is taken as an indication that the Virgin agricultural strategy didn't change much during the course of their occupation.

Chronology

There are presently 63 radiocarbon assays reported from sites on the entire Grand Staircase physiographic section in Utah (McFadden, on file Kanab BLM office). These dates demonstrate a continuous sequence of occupation from the 1st century B.C. through the 13th century. Thirty-six of the dates are from sites located in the Monument (Figure 3). Although the sample is relatively small, it

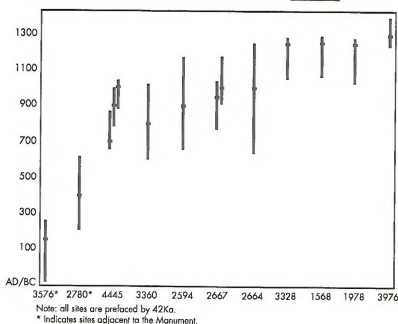


Figure 3. Selected Formative period radiocarbon dates on the Grand Staircase section of the GSENM (2 sigma range with calibrated midpoints).

demonstrates that the sequence of Anasazi occupation in the Monument is well-represented. In addition, material culture traits from each period closely parallel the sequence found outside the Monument; this permits cross-dating through comparison of ceramic styles, projectile point types, and architectural styles found elsewhere in the Virgin culture area.

The Virgin Settlement Pattern

Although the Virgin architectural sequence varies stylistically through time, site size and function appear to remain about the same throughout the sequence. During the Basketmaker period, scattered slab-lined cists and a pithouse make up the residential unit. By the Pueblo I period, layouts take on a crescent shape of individual cists with masonry upper walls and a pithouse located to the south. During Pueblo times, these subterranean structures were replaced with surface masonry or jacal roomblocks incorporating both storage and residential rooms. Both crescent shaped and linear pueblos occur during the late Pueblo II and Pueblo III periods. Interestingly, pitstructures during the latest period are fully subterranean, similar to kivas in the Kayenta area, but lacking formal kiva features.

These late architectural innovations and associated material culture introductions are part of the Kayenta influence or "Pueblo II expansion" (Aikens, 1966) that occurs throughout the Monument about A.D. 1100 (McFadden, 1996). Recently, the "intellectual productivity" of making a distinction between the Virgin and Kayenta traditions has been questioned (Euler, 1994). I maintain that it is useful, if only to distinguish separate populations; e.g., if the "influence" represents a migration event, it could have had a profound effect on the Virgin settlement-subsistence strategy and may have contributed to the final abandonment of the area during the 13th century.

Sites on the Grand Staircase tend to occur in clusters that probably represent dispersed communities. Site size indicates that the nuclear or perhaps extended family was the basic social unit during all periods. In the Seaman Wash area, these sites span a period of 1,000 years demonstrating an impressive temporal continuity; social cohesiveness and continuity is also demonstrated by the ceramics they used—the distribution of Shinarump series ceramics seems to coincide very closely with the boundaries of the Monument.

Virgin farmsteads are virtually always located adjacent to arable soils; essentially they function as full-time field houses tethered to their primary resource base—the agricultural field. A good measure of their long-term agricultural success is the number and volume of storage rooms found on these sites.

The most striking characteristic of Virgin sites in the Grand Staircase, as well as the St. George Basin, is their complexity; this results from being accretionally constructed and later remodeled, then abandoned, only to be rebuilt once again during a later episode of occupation (Dalley and McFadden, 1985; McFadden, 1996). This kind of site formation process is



not uncommon in the southwest, but its ubiquity in the Grand Staircase suggests a conscious process, rather than simply opportunistic reoccupation. The Arroyo site (42Ka3976) in Kitchen Corral drainage, provides an outstanding example of this type of phenomenon. This late Pueblo II site was constructed on an alluvial fan, buried by over 1 meter of outwashed sediments, and was recently reexposed by the same wash. The arroyo cut revealed both sequentially occupied pithouses and a roomblock that had been remodeled several times. If the Arroyo site was located to take advantage of this floodwater farming opportunity, the same natural process of periodic devastating floods may account for the site's apparent episodes of abandonment and reoccupation.

The Virgin Adaptive Strategy—A Model

The practice of agriculture on the Grand Staircase was not without risk. Several recent interdisciplinary investigations bear this out: tree-ring studies have demonstrated that agriculturists would have had to contend with both short- and long-term fluctuations in precipitation (Gumerman, 1988; Larson, 1990); geological studies have demonstrated that arroyo downcutting and filling episodes would also have had serious consequences for agriculture (Hereford, 1986; Webb et al., 1991; Kulp, 1995) I suggest (McFadden, 1996) that the Virgin pattern of settlement in the Grand Staircase reflects an adaptive strategy aimed at reducing risk by alternating occupation between multiple residential sites that were located in a variety of different agricultural niches. This hypothesis accounts for both the internal site pattern of episodic occupation, as well as the distribution of sites in diverse settings across the landscape. These shifts in residence, from one area to another, would have occurred in response to a variety of circumstances, including: the deterioration of agricultural fields through headward entrenchment, lack of winter moisture, summer floods, soil nutrient depletion, bug infestation or firewood depletion—all could induce the

temporary abandonment of fields for unaffected locations nearby.

The Fremont

Fifty miles northeast of the Grand Staircase, across the Kaiparowits Plateau, and located in the Escalante River drainage system, is evidence of a second Formative culture known as the Fremont. The Fremont occupied a vast area in Utah north of the Anasazi culture area. Although the Fremont were contemporary with the Virgin Anasazi and they possessed similar abilities in the realm of ceramic and lithic technology, architecture, and horticulture, they developed a very distinct adaptation to this unique part of the southwest. Fremont settlement patterns—that is, the distribution of different types of sites over the landscape—reflect a way of life dramatically different from that of the Virgin Anasazi. The virtual absence of evidence for contact between the Virgin Anasazi and the Escalante Fremont provides an exceptional opportunity to investigate parallel local adaptations in the Monument.

Previous Investigations

The first concerted effort to investigate the Fremont in the Escalante basin was made by the University of Utah in the late 1950's and early 1960's as part of the Glen Canyon Project (Gunnerson, 1959a; Lister, 1964). Recently, additional inventory in Glen Canyon has built upon this earlier work and demonstrated the Fremont occupation of the canyons to be considerably earlier and longer than previously thought (Geib, 1996). Unfortunately, both of these investigations were hampered by being restricted to the special geographical/environmental setting of the nearby Glen Canyon National Recreation Area—only rarely do prehistoric settlement patterns correspond with the administrative boundaries of Federal agencies. An in-house inventory on adjacent BLM lands, now within the Monument, has recently been undertaken to provide a more complete picture of Fremont settlement (McFadden, 1997).



Residential Architecture

The most obvious disparity between Fremont occupation in the Monument and in Glen Canyon is the lack of residential sites in the canyons where agriculture was being practiced (Gunnerson, 1959a; Gieb, 1996). While only a few residential sites have been recorded in the recreation area (Geib, 1996), approximately 75 have been recorded in the uplands of the Monument (McFadden, 1997). Material culture traits, particularly ceramics, indicate that these pithouse and surface masonry sites are related to the San Rafael Fremont. Many of them occur along perennial streams in the vicinity of Escalante and have been assumed to be primarily farmsteads (Gunnerson, 1959a). This is possible, but in marked contrast to the Virgin Anasazi pattern, and also the San Rafael rancheria pattern (Jennings, 1978), these sites do not have on-site storage facilities—which is the hallmark of sedentary agriculture. Recent inventory in the Big Flat locality and elsewhere in the uplands suggests that the majority of Fremont residences are located in nonarable settings and appear not to have on-site storage. How can this nonagricultural pattern be reconciled with the findings in the Recreation Area, where the Fremont were considered to have relied heavily on agriculture (Fowler, 1963; Geib, 1996)?

Storage Architecture

Reliance on agriculture involves surplus, and surplus requires storage—a good measure of a group's reliance on agriculture may be determined by the location and volume of storage space available for surplus. Fremont agricultural storage in the Escalante drainage was primarily in granaries. These structures range in size from not much bigger than a breadbox to being capable of holding many bushels, but compared to the Virgin Anasazi, Fremont storage capacity is minuscule. Gunnerson (1959a) suggested granaries functioned to store seed corn rather than surplus. Their location, often hundreds of feet above the canyon floors, concealed in locations difficult to access, and particularly their remoteness from residential structures, implies a much different logistical organization for the Fremont than that proposed for the Virgin Anasazi.

Chronology

Six recently obtained ^{14}C dates from Fremont granaries and sheltered sites fall within a range between A.D. 650 and 1025 (2 sigma, 95 percent probability) (Figure 4). These dates correspond well with ceramically cross-dated pithouse sites that display Emery gray ware, a type that dates between A.D. 700 and 1200 (Madsen, 1977) or perhaps as early as A.D.

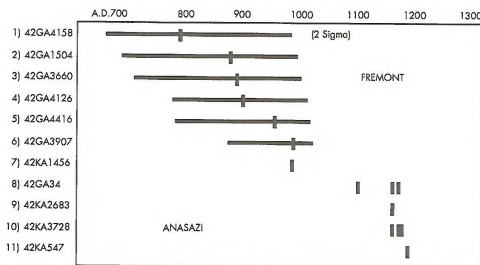


Figure 4. Radiocarbon calibrated midpoints and tree-ring dates from the Kaiparowits Plateau and Escalante drainage.



400-550 (Geib, 1996). Figure 5 shows the distribution of both granaries and residential sites in the upper Escalante drainage. Although additional dating needs to be done, it appears that both types of sites are roughly contemporary and may well be part of a single settlement pattern.

Escalante Fremont Adaptation—A Model

Based on this pattern of separate distributions for storage and residential sites, a model of Fremont settlement-subsistence practices can be proposed. Seasonal mobility was the basis for Fremont adaptation in the Escalante; during the summer, camps were occupied in the

perennially watered canyons below 7,000 feet (2134 m) primarily to farm; during winter, the uplands were occupied to hunt migratory mule deer and exploit an abundant source of firewood. Concealed storage granaries facilitated this mobile lifeway by securing seed corn for the following year, as well as by providing short-term storage during their absence.

This model requires testing and will surely be modified, but the contrast between Virgin Anasazi and Fremont settlement patterns demonstrates that within the Monument, two very different adaptations coexisted—each was conditioned by the group's cultural background, yet each was also a response to its environmental setting.

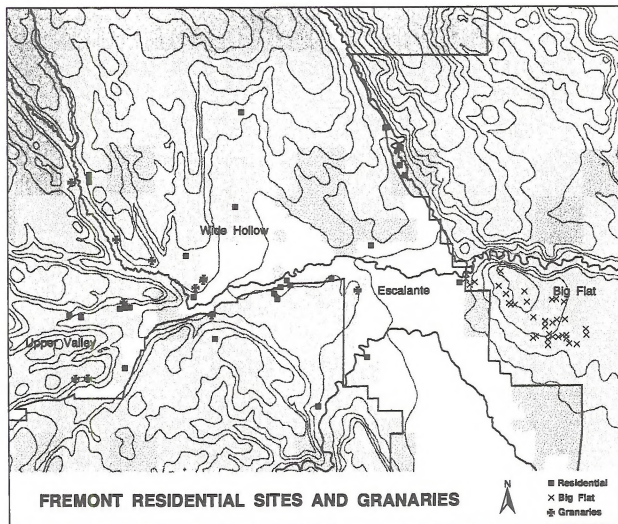


Figure 5. Distribution plot of residential sites, granaries, and the Big Flat site cluster, upper Escalante drainage.



The Kaiparowits Plateau

The third major physiographic area in the Monument, and perhaps the second most densely occupied during the Formative period, is the Fifty-mile Mountain portion of the Kaiparowits Plateau. Fifty-mile Mountain lies along the eastern escarpment of the Kaiparowits and overlooks the Escalante Desert nearly 2,000 feet (609 m) below. At 7,000 feet (2134 m), it receives annual precipitation of over 12 inches (30 cm) and has numerous springs. Broad sagebrush-filled valleys offer deep soils that provide an upland setting conducive to Anasazi dryfarming. The Plateau also provides significant big game habitat—particularly winter range for mule deer, the favored game of the Fremont (Dalley, 1970; Jennings, 1978).

Early Research and Interpretation

One of the prerequisites of the University of Utah's research in Glen Canyon was the need to "...develop comparative material outside Glen Canyon in order to better understand the latter collections" (Jennings, 1966).

Accordingly, in the summer of 1958, 255 mostly Puebloan architectural sites were recorded and plotted on a plane table map (Gunnerson, 1959b). In 1961, an additional 49 sites were added to the inventory and 11 sites were excavated (Fowler and Aikens, 1963).

The upgrading of site forms and replotting of these sites on 7.5-minute quadrangle maps has been an ongoing process (Figure 6). Since the early 1970's, about 100 additional sites have been recorded, bringing the total to over 400.

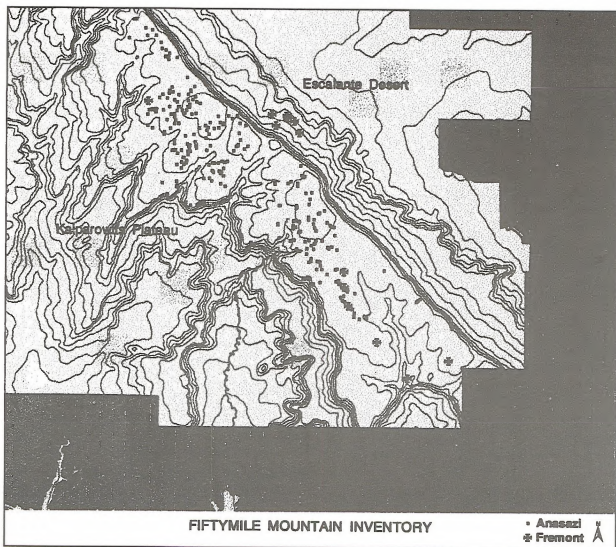


Figure 6. Fifty-mile Mountain Anasazi and Fremont site distributions.



Based largely on the interpretation of ceramics (Lister, 1964) the Fiftymile Mountain occupation was viewed as "...the result of a direct northward extension of Kayenta culture bearers from the Tsegi Canyon region of northern Arizona." Based on ceramics, the period of occupation was estimated to have been between A.D. 1050 and 1250 (Fowler and Aikens, 1963). Fremont ceramics were eventually recognized, but little evidence for intensive occupation was found on the Plateau (Fowler and Aikens, 1963). Only a single slab-lined pithouse with Fremont ceramics was recorded and a mere 8 percent of the total ceramic collection was classified as Fremont. Basically, there just wasn't enough evidence to say much about the relationship between the Fremont and the Anasazi. Lister (1964) did, however, recognize the Kayenta occupation as atypical, observing that it was "some sort of local provincialism, which cannot yet be discretely defined." In his synthesis of the Glen Canyon Project, Jennings (1966) considered the architectural and ceramic evidence at Coombs (and presumably the Kaiparowits) to indicate that "the populations blended," or were in "intimate contact" (Jennings, 1966).

Discussion

Since the Glen Canyon Project, several investigations along the Fremont-Anasazi interface have encountered sites and groups of sites with mixed or "blended" material culture traits that have presented interpretive problems (Jennings and Sammons-Lohse, 1981; Madsen, 1989). Madsen (1997) has suggested that the Fremont and Anasazi "merely represented opposite ends of a social continuum." He contends "agricultural peoples in the monument area might well be called 'Freazi' or 'Anamont' due to similarities to groups to the north and south" (Madsen, 1997).

This is clearly not the case for the Virgin and Fremont manifestations in the Monument that can be readily characterized as special adaptations to their unique local environments. While each of these adaptations selectively drew on its own cultural heritage for material traits and items, the adaptation itself is essentially

behavioral—actually, a strategy to organize behavior: the Virgin were sedentary farmers who practiced residential mobility; the Escalante Fremont strategy was seasonally mobile and involved hunting/gathering as well as agriculture. If describing adaptive behavior is our goal, the Freasi-Anamont conundrum is put in a different perspective: material culture traits can be assessed in terms of how they contributed to the success of a group's adaptive strategy, rather than which end of the social continuum they represent.

Recent Research

Our understanding of Kaiparowits prehistory has not progressed much since Jennings' (1966) synthesis. The bewildering variety of architecture and the apparent "blends" of Fremont and Anasazi artifacts on the Plateau seem to defy interpretation beyond simply inferring "intimate contact" (Jennings, 1966). They could indicate that the Fremont predated the Anasazi, were quickly displaced by them, were rapidly acculturated, or living in harmony—perhaps with a mutually beneficial adaptive strategy.

Recent investigations on Fiftymile Mountain have attempted to better define the "Anasazi" settlement pattern (Aikens, 1962; Gunnerson, 1959a), and also to determine whether a separate Fremont pattern can be defined. Simultaneously, we are developing a chronology based on radiocarbon and tree-ring dates to determine if the two occupations are contemporary or sequential.

Chronology

Gunnerson (1959b) believed that "most if not all of the Fremont occupation was apparently contemporaneous with the most intensive occupation of the Kaiparowits area." This was based solely on ceramic cross-dating—the Glen Canyon Project was successful in obtaining only a single tree-ring date from the Plateau.

Based on a recently obtained sequence of radiocarbon dates from the lowlands in Glen



Canyon, Geib (1996) has shown the Fremont occupation in the region to have begun much earlier than previously thought. Relevant to this discussion, the Glen Canyon sequence appears to end about A.D. 1000—well before the Anasazi are thought to have entered the area. Geib concludes that “...there is little evidence to support the interpretation of Fremont and Anasazi coexistence....” Additional dates could, of course, extend the sequence.

The only two probable Fremont dates from Fiftymile Mountain are a tree-ring date of A.D. 980v from 42Ka1456, a masonry room located on the rim of Harveys Fear and a radiocarbon date (Beta 107650) with a calibrated midpoint of A.D. 905, 920, and 950 from a free-standing granary (42Ka4416) on the north end of the Plateau. These dates correspond well with Fremont dates in the Escalante area (Figure 4). Our efforts at chronometric dating will likely extend the Fremont chronology into the 11th century, but for now it is interesting to note just how extensive (and variable) Fremont granaries were just prior to the arrival of the Anasazi.

The five tree-ring dates presently available from Anasazi sites on Fiftymile Mountain were collected from four sites (Figure 4). These cutting dates tightly cluster between A.D. 1149 and 1189—about the same range as Coombs Village. They were collected from both storage and residential structures. Additional specimens have been submitted for dating, and the original Glen Canyon Project collections are being reexamined to see if they can be dated with recently developed chronologies. At present however, there remains a 150-year gap between the latest Fremont and the earliest Anasazi date on the Plateau.

Settlement Patterns

A few Fremont style slab-lined pithouses were recorded by the University of Utah, but they were never numerous enough to establish a pattern. Recent inventory has identified 10 or so additional slab-lined, as well as boulder-lined, structures widely spread over the Plateau. If

the dated granaries are actually associated with them, we have the basis for a more complete description of the upland Fremont settlement pattern. This raises the question of what pattern is represented: the seasonal upland hunting adaptation, or an undefined, upland dryfarm adaptation?

Aikens (1962) and Gunnerson (1959b) described the Anasazi settlement pattern on Fiftymile as one of dispersed hamlets, with one to four rooms, located on ridges and knolls near arable land. Storage rooms were assumed to be on-site, but granaries were also noted in alcoves. They did not speculate on how often remote storage structures were used. They believed the Anasazi were fully sedentary and occupied the Plateau on a full-time basis.

A review of the University of Utah excavation data, combined with observations based on recent inventory, raises questions about the interpretation of the Kaiparowits occupation as full-time and sedentary. Deposits at all 11 of the excavated sites were shallow, unstratified, and had virtually no midden development. The lack of occupational intensity is demonstrated by a meager (by Anasazi standards) sherd count of 5,244 for all 11 excavated sites. Although several of the pueblos were impressively large, they appear to be lightly constructed—perhaps more conducive to summer habitation. Seasonal occupation is also supported by the lack of indoor hearths. Actually, formal slab-lined hearths were more common outside of structures. The best candidate for a winter residence was an intensively used pithouse at the Golden Stairs site—a structure suggestive of the earlier Fremont style.

The most unusual characteristic of Kaiparowits settlement is the degree of reliance on storage in isolated granaries. These architectural marvels are well-constructed of masonry with tightly fitted sandstone slab doors set in clay copings. They occur individually or in clusters of up to six. Although residential structures are also known to occur in alcoves, rarely are they associated with storage, and both are often located a considerable distance



from the nearest arable land. Unlike many Fremont granaries, these structures are large-volume and obviously intended for surplus. Most strikingly, they are located in ingeniously concealed and inaccessible overhangs situated around the rim of the Plateau—accessible overhangs are numerous, but apparently were not considered suitable. Although similar granaries can be found throughout the Colorado Plateau, nowhere do they occur in such great numbers.

Conclusion

If the emerging site distribution patterns on Fiftymile Mountain are considered in terms of behavior—i.e., as indications of seasonal use, mobility, perhaps even hostility—they appear to represent a very distinctive Anasazi settlement pattern occurring in an area previously, and perhaps simultaneously, occupied by the Fremont. Rather than dwelling on just who these people were, I suggest we first attempt to understand the pattern on Fiftymile Mountain as one more essentially unique adaptation in the Monument.

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Proveniencing Intrusive Trade Ware and Local Pottery by Magnetic Susceptibility Measurements, Geochemical and Petrographic Analysis: The Coombs Site, 42GA34

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ABSTRACT

■ A large pottery assemblage available at the Coombs site (A.D. 1050-1200), located in south-central Utah in the northeastern quadrant of the Grand Staircase-Escalante National Monument, affords an opportunity to source Tusayan gray and white wares, Mesa Verde white ware, San Juan white and red wares, Tsegi orange ware, and Utah Desert white ware. The site is limited in the variety of natural temper and paste resources available. Consequently, locally produced pottery temper is dominated by quartz sands and basalt. The unique petrographic and geochemical aspects of the Coombs pottery varieties are a function of the basaltic temper. Using the geochemical and petrographic investigations of the local Coombs wares, we provide compositional data on the Kayenta core area, Fremont, Mesa Verde, and Virgin area intrusive pottery. Petrographic and geochemical analysis of ceramic wares from contemporary sites within the Monument can be used to examine the cultural context of the Coombs villagers with respect to others who comprised the late Anasazi occupations of southern Utah.

The Coombs site, 42GA34, is located in Boulder, Utah, along Highway 12 in the

south-central portion of the State (Figure 1). It is situated in an alluvial fan on the southern slope of the Aquarius Plateau between Boulder Mountain and the canyon lands of the Escalante River at an elevation of about 6,700 feet. The site (Anasazi State Park) is administered by the State of Utah, Department of Natural Resources, Division of Parks and Recreation. There have been a variety of excavations at the site (Prince, 1993), all of which have produced a significant quantity of

ceramics which are housed in the museum at the park. It is from this collection of material that the analyses here are performed. In 1994, geological test pits were dug to ascertain the sediment composition at the site. Grain size and composition analysis were made in addition to other measurements, and in 1997, additional field samples were collected from the site and neighborhood to acquire raw materials for sourcing characterization.

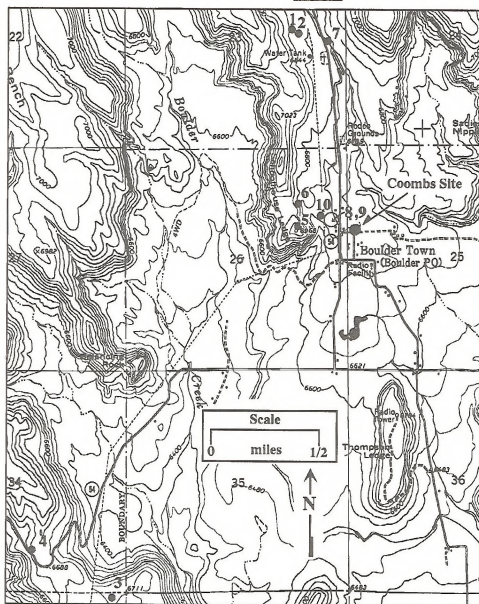


Figure 1. Location of source samples near Coombs site.

Analytical Methods

A total of 202 ceramic sherd samples and 35 source samples were studied. Of the 202 sherds, 51 were studied (Table 1) with very detailed petrographic and geochemical analysis. A total of 19 source samples (Table 1) were also geochemically analyzed out of the 35 samples that were studied. Some of these source samples are located near the Coombs site (Figure 1). The remaining ceramic sherds (149 samples) were analyzed by standard petrographic analysis for basic identification of

temper and inclusions. Magnetic susceptibility measurements were made on all ceramic sherds and source samples.

For geochemical analysis, 1 gram of each sample was crushed by ceramic mortar and was sent directly to the analytical laboratory (XRAL) for neutron activation (NA) analysis. A total of 34 elements were obtained on each sample. Neutron activation analysis was chosen since it is possible to obtain chemical data on rare earth elements, which are partitioned differently in basaltic rocks than in granitic rocks. This is an important consideration since basaltic temper is used at the Coombs site, and therefore it is possible that

the rare earth elements (La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu) can provide a means of discrimination.

Magnetic susceptibility (k) as reported in Carmichael (1989) is the ease of magnetization of a material in an external field. Magnetic susceptibility may also be thought of as the ability of a volume of a material to enhance the local magnetic field. In general terms it is: $k = J/H$, where: k = magnetic susceptibility, J = total magnetization (if induced magnetization then = I), and H = ambient field intensity. Magnetic susceptibility data



Table 1. Sample numbers.

Tradition	Series	Class	FS Number	Laboratory Number
Tusayan Gray Ware	Tsagi	Moenkapi Corrugated	1197/513	1
		Moenkapi Corrugated (Coombs Variety)	676/64	2
		Tusayan Corrugated (Coombs Variety)	1733/1142	3
		Coombs Gray	550/18	4
		Coombs Gray polished	1149	5
		Gray stily	143/32	6
	Virgin	Tusayan Corrugated	563/6	7
		Kia Stiel Gray	1583/13	8
		North Creek Corrugated	214/252	9
		North Creek Fugitive Red	1426/5	10
		Gray Ware, rock temper	864/14	11
		Johnson	Johnson Corrugated	1196/69
Tusayan White Ware	Kayenta	Gray Ware, sand and sherd	550/138	13
		Gray Ware, crushed rock and sherd	30/20	14
		Garfield B/W	1145/139	15
		Black Mesa B/W	1100/10	16
		Black Mesa B/W	563/123	17
		Soti B/W	1367/95	18
	Puerco	Onagawa B/W	1423/118	19
		Flagstaff B/W	1100/115	20
		Wupatki B/W	1043/112	21
		Tusayan White Wares	1513	22
		Shots B/W	644/213	23
		McElmo B/W	1535/3	24
Mesa Verde White Ware		Unid.	824/106	25
San Juan White Ware		Padre B/W	1546/8	26
Cibola White Ware	Puerco	Galup B/W	1700/20	27
		Escavado B/W	554/44	28
San Juan Red Ware	Little Colorado	Puerco B/W	1472/20	29
		Deadmans B/R	766/1050	30
		Middleton Red	1181/28	31
		Middleton Red	214/132	32
		Middleton B/R	1013/12	33
		Middleton Polychrome	1280/7	34
	Tsagi	Unidentified Tsagi Orange Ware	227/382	35
		Medicine B/R	949/58	36
		Tusayan B/R	221/1	37
		Tusayan B/R (Coombs Variety)	949/46	38
		Tusayan Polychrome	550/51	39
		Cibola Polychrome	219/13	40
Utah Desert Gray Ware	Fremont	Cibola Polychrome (Coombs Variety)	473/19	41
		Tsagi R/O	220/75	42
		Tsagi R/O (Coombs Variety)	226/23	43
		Tsagi Orange (Coombs Variety)	949/55	44
		Tsagi Orange	220/29	45
		Cameron Polychrome	55/60	46
	Great Salt Lake	Cameron Polychrome (Coombs Variety)	122/2	47
		Emery Gray	219/32	48
		Emery Toiled	439/17	49
		Sevier Gray	226/481	50
		Ivix Creek	554/4	51
Source Samples				
Basalt, weathered, Test Pit 1, backfill debris, pebble, 42GA34				GTR-20
Basalt, weathered, Test Pit 1, backfill debris, pebble, 42GA34				GTR-21
Basalt, weathered, Test Pit 1, backfill debris, pebble, 42GA34				GTR-22
Basalt, weathered, Test Pit G01, Layer II, pebble, 42GA34				GTR-23
Basalt, fresh, Test Pit G01, Layer II, pebble, 42GA34				GTR-24
Basalt, fresh, Test Pit G01, Layer II, pebble, 42GA34				GTR-24
Basalt, fresh, Test Pit G01, Layer III, pebble, 42GA34				GTR-25
Basalt, fresh, Test Pit G01, Layer III, pebble, 42GA34				GTR-27
Clastic sandstone pebble, Test Pit 1, backfill debris, pebble, 42GA34				GTR-28
Test Pit G01, surface, Layer I, fine sand, mostly quartz, 42GA34				GTR-16
Test Pit G01, 25-30 cm, Layer 2, fine sand and very coarse sand, quartz, 42GA34				GTR-17
Test Pit G01, 65 cm, Layer III, fine sand and very coarse sand, quartz+V8, 42GA34				GTR-18
70N402 E, Layer 1, 0-5 cm, A Horizon, fine sand & very coarse sand, 42GA34				GTR-29
70N402 E, Layer 2, 10-15 cm, B1 Horizon, fine sand & very coarse sand, 42GA34				GTR-30
70N402 E, Layer 3, 20-25 cm, B4 Horizon, fine sand, 42GA34				GTR-31
70N402 E, Layer 3, 30-35 cm, B4 Horizon, fine sand, 42GA34				GTR-32
70N402 E, Layer 4a, 45-50 cm, B/C Horiz., fine sand & very coarse sand, 42GA34				GTR-33
70N402 E, Layer 4b, 70-75 cm, C Horizon, fine sand, 42GA34				GTR-34
70N402 E, Layer 4b, 105-110 cm, C Horizon, fine sand, 42GA34				GTR-35
Clay sample, Carmel Formation, water table				GTR-01
Clay sample, Carmel Formation, borrow area				GTR-02
Clay sample, Carmel Formation, dune				GTR-03
Sandstone sample, Carmel Formation				GTR-04
Clay sample, Carmel Formation, School House Ledge				GTR-05
Sandstone sample, Navajo Formation, School House Ledge				GTR-06
Quartzite sample, clastic pebble, W. Over Creek				GTR-07
Basalt sample, clastic pebble, weathered surface				GTR-08
Basalt sample, rectangular fragment				GTR-09
Basalt sample, rectangular fragment				GTR-10
Clay sample, Oakdale Sandstone, Hurricane				GTR-11
Clay sample, Oakdale Sandstone, Escalante, Wildlife Junction				GTR-12
Clay sample, Chinle Formation, Burr Trail, (gray)				GTR-13
Clay sample, Chinle Formation, Burr Trail, (brown)				GTR-14
Clay from burial, 42GA34				GTR-15
Clay sample, pit, C. Ricks', western side of School House Ledge				GTR-19



were collected using a *Kappameter* (KT-5c) remote sensing susceptibility meter at an operating frequency of 10 kHz. The sensitivity of the unit is 1×10^{-5} SI units or 0.8×10^{-3} cgs. One (1.0) SI unit (or a volume susceptibility of about 3×10^{-3} cgs) is approximately equivalent to 1 percent magnetite by weight (Breiner, 1973). We report magnetic susceptibility as the actual laboratory measurements, and per unit gram weight.

Petrographic analysis of each sample was accomplished using standard principles (Williams et al., 1954; Pettijohn, 1949; Folk, 1968; Huang, 1962; Jones and Fleming, 1965; Tickell, 1965; Moorhouse, 1959; and Kerr, 1977). Mineralogic identifications and modal analysis were made using both polished and unpolished sections set up on a binocular microscope with reflected light. Consequently, grain shape and size data could be collected along with grain surface texture data. Modal data collection utilized a 0.25mm traverse grid spacing. Minerals requiring conoscopic observations for identification were hand-picked from the polished section and made into a grain mount for polarized light observations.

Results

Results of the petrographic examination are located in Table 2. The chemical analyses for the ceramic sherds are provided in Table 3 and for the source materials in Table 4. Detection limits are provided for each of the elements studied. The magnetic susceptibility data is provided in Table 5, along with general petrographic data for all of the sherds studied (202 sherds). Magnetic data is also provided for the 35 source samples (Table 4).

Coombs variety sherds have generally higher magnetic susceptibility values than their corresponding Class imports. This can be summarized for the average magnetic susceptibility/gram measurements as follows: Moenkopi corrugated imports = 0.0836, and the Coombs variety = 0.1088; Tusayan corrugated

imports = 0.0585, and the Coombs variety = 0.1381; Tusayan black/red imports = 0.0462, and the Coombs variety = 0.1304; Tusayan polychrome imports = 0.0708, and the Coombs variety = 0.1898; Citadel polychrome imports = 0.0501, and the Coombs variety = 0.1882; Tsegi red/orange imports = 0.0547, and the Coombs variety = 0.1493; Tsegi orange imports = 0.1335, and the Coombs variety = 0.1577 (these are fairly similar in value); and Cameron polychrome imports = 0.0726, and the Coombs variety = 0.1353.

Although we have investigated numerous scattergram plots of chemical, petrographic, and magnetic susceptibility data, we have chosen a few of these that best represent the field of sample data that exists. These include magnetic susceptibility vs. Th/U (Figure 2A), Fe vs. Zn (Figure 2B), Ca vs. Na (Figure 2C), and crushed rock vs. Na (Figure 2D). Figure 3 deals with the rare earths (La + Ce + Nd) vs. (Th + Cs + Hf).

Figure 2A utilizes magnetic susceptibility vs. Th/U ratio. In this scattergram, the magnetic susceptibility, or in a rough sense the iron mineral content, is compared to the thorium to uranium ratio. The iron mineral content should be higher in the temper than in the paste, although both materials will have magnetite concentrations (Table 4, magnetic susceptibility of the source materials). The thorium to uranium ratio of the average crustal rocks of the earth is about 3.5 to 3.6 (Carmichael, 1989) and this value is similar for either granites or basalts. Values much greater than 4.5 indicate a significant excess of thorium over uranium, and values much under 2.5 indicate a significant excess of uranium over thorium. In Table 4, the Th/U ratio is given for the source samples. These samples divide into essentially two categories: a normal crustal ratio (2.83 to 4.58) for the Carmel Formation and for the basalt samples, and a significantly depleted thorium ratio (less than unity) for the Navajo Sandstone, Dakota Formation, Chinle Formation, the local Coombs site sediments, clay from the interior of a pot, and the burial clay sample from the Coombs site.

**Table 2.** Petrography summary.

Year	Month	Day	Time	Location	Event	Category	Score	Rank	Notes
1970/10	October	10	10:00	London	World Cup	Football	100	1	Final
1971/01	January	15	15:00	Paris	Championnat	Football	120	2	Final
1972/05	May	20	20:00	Berlin	Weltmeisterschaft	Football	150	3	Final
1973/08	August	25	25:00	Rome	Coppa Italia	Football	180	4	Final
1974/11	November	30	30:00	Stockholm	VMK	Ice Hockey	200	5	Final
1975/03	March	10	10:00	Vienna	Weltmeisterschaft	Ice Hockey	250	6	Final
1976/06	June	18	18:00	Montreal	Jeux Olympiques	Summer	300	7	Final
1977/09	September	22	22:00	Prague	MSV	Handball	350	8	Final
1978/12	December	28	28:00	Calgary	Winter Olympics	Winter	400	9	Final
1979/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	450	10	Final
1980/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	500	11	Final
1981/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	550	12	Final
1982/01	January	30	30:00	Calgary	Winter Olympics	Winter	600	13	Final
1983/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	650	14	Final
1984/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	700	15	Final
1985/11	November	30	30:00	Calgary	Winter Olympics	Winter	750	16	Final
1986/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	800	17	Final
1987/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	850	18	Final
1988/09	September	22	22:00	Prague	MSV	Handball	900	19	Final
1989/12	December	28	28:00	Calgary	Winter Olympics	Winter	950	20	Final
1990/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	1000	21	Final
1991/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	1050	22	Final
1992/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	1100	23	Final
1993/01	January	30	30:00	Calgary	Winter Olympics	Winter	1150	24	Final
1994/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	1200	25	Final
1995/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	1250	26	Final
1996/11	November	30	30:00	Calgary	Winter Olympics	Winter	1300	27	Final
1997/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	1350	28	Final
1998/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	1400	29	Final
1999/09	September	22	22:00	Prague	MSV	Handball	1450	30	Final
2000/12	December	28	28:00	Calgary	Winter Olympics	Winter	1500	31	Final
2001/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	1550	32	Final
2002/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	1600	33	Final
2003/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	1650	34	Final
2004/01	January	30	30:00	Calgary	Winter Olympics	Winter	1700	35	Final
2005/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	1750	36	Final
2006/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	1800	37	Final
2007/11	November	30	30:00	Calgary	Winter Olympics	Winter	1850	38	Final
2008/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	1900	39	Final
2009/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	1950	40	Final
2010/09	September	22	22:00	Prague	MSV	Handball	2000	41	Final
2011/12	December	28	28:00	Calgary	Winter Olympics	Winter	2050	42	Final
2012/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	2100	43	Final
2013/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	2150	44	Final
2014/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	2200	45	Final
2015/01	January	30	30:00	Calgary	Winter Olympics	Winter	2250	46	Final
2016/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	2300	47	Final
2017/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	2350	48	Final
2018/11	November	30	30:00	Calgary	Winter Olympics	Winter	2400	49	Final
2019/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	2450	50	Final
2020/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	2500	51	Final
2021/09	September	22	22:00	Prague	MSV	Handball	2550	52	Final
2022/12	December	28	28:00	Calgary	Winter Olympics	Winter	2600	53	Final
2023/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	2650	54	Final
2024/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	2700	55	Final
2025/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	2750	56	Final
2026/01	January	30	30:00	Calgary	Winter Olympics	Winter	2800	57	Final
2027/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	2850	58	Final
2028/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	2900	59	Final
2029/11	November	30	30:00	Calgary	Winter Olympics	Winter	2950	60	Final
2030/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	3000	61	Final
2031/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	3050	62	Final
2032/09	September	22	22:00	Prague	MSV	Handball	3100	63	Final
2033/12	December	28	28:00	Calgary	Winter Olympics	Winter	3150	64	Final
2034/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	3200	65	Final
2035/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	3250	66	Final
2036/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	3300	67	Final
2037/01	January	30	30:00	Calgary	Winter Olympics	Winter	3350	68	Final
2038/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	3400	69	Final
2039/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	3450	70	Final
2040/11	November	30	30:00	Calgary	Winter Olympics	Winter	3500	71	Final
2041/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	3550	72	Final
2042/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	3600	73	Final
2043/09	September	22	22:00	Prague	MSV	Handball	3650	74	Final
2044/12	December	28	28:00	Calgary	Winter Olympics	Winter	3700	75	Final
2045/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	3750	76	Final
2046/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	3800	77	Final
2047/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	3850	78	Final
2048/01	January	30	30:00	Calgary	Winter Olympics	Winter	3900	79	Final
2049/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	3950	80	Final
2050/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	4000	81	Final
2051/11	November	30	30:00	Calgary	Winter Olympics	Winter	4050	82	Final
2052/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	4100	83	Final
2053/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	4150	84	Final
2054/09	September	22	22:00	Prague	MSV	Handball	4200	85	Final
2055/12	December	28	28:00	Calgary	Winter Olympics	Winter	4250	86	Final
2056/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	4300	87	Final
2057/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	4350	88	Final
2058/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	4400	89	Final
2059/01	January	30	30:00	Calgary	Winter Olympics	Winter	4450	90	Final
2060/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	4500	91	Final
2061/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	4550	92	Final
2062/11	November	30	30:00	Calgary	Winter Olympics	Winter	4600	93	Final
2063/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	4650	94	Final
2064/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	4700	95	Final
2065/09	September	22	22:00	Prague	MSV	Handball	4750	96	Final
2066/12	December	28	28:00	Calgary	Winter Olympics	Winter	4800	97	Final
2067/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	4850	98	Final
2068/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	4900	99	Final
2069/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	4950	100	Final
2070/01	January	30	30:00	Calgary	Winter Olympics	Winter	5000	101	Final
2071/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	5050	102	Final
2072/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	5100	103	Final
2073/11	November	30	30:00	Calgary	Winter Olympics	Winter	5150	104	Final
2074/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	5200	105	Final
2075/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	5250	106	Final
2076/09	September	22	22:00	Prague	MSV	Handball	5300	107	Final
2077/12	December	28	28:00	Calgary	Winter Olympics	Winter	5350	108	Final
2078/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	5400	109	Final
2079/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	5450	110	Final
2080/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	5500	111	Final
2081/01	January	30	30:00	Calgary	Winter Olympics	Winter	5550	112	Final
2082/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	5600	113	Final
2083/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	5650	114	Final
2084/11	November	30	30:00	Calgary	Winter Olympics	Winter	5700	115	Final
2085/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	5750	116	Final
2086/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	5800	117	Final
2087/09	September	22	22:00	Prague	MSV	Handball	5850	118	Final
2088/12	December	28	28:00	Calgary	Winter Olympics	Winter	5900	119	Final
2089/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	5950	120	Final
2090/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	6000	121	Final
2091/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	6050	122	Final
2092/01	January	30	30:00	Calgary	Winter Olympics	Winter	6100	123	Final
2093/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	6150	124	Final
2094/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	6200	125	Final
2095/11	November	30	30:00	Calgary	Winter Olympics	Winter	6250	126	Final
2096/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	6300	127	Final
2097/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	6350	128	Final
2098/09	September	22	22:00	Prague	MSV	Handball	6400	129	Final
2099/12	December	28	28:00	Calgary	Winter Olympics	Winter	6450	130	Final
2100/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	6500	131	Final
2101/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	6550	132	Final
2102/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	6600	133	Final
2103/01	January	30	30:00	Calgary	Winter Olympics	Winter	6650	134	Final
2104/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	6700	135	Final
2105/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	6750	136	Final
2106/11	November	30	30:00	Calgary	Winter Olympics	Winter	6800	137	Final
2107/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	6850	138	Final
2108/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	6900	139	Final
2109/09	September	22	22:00	Prague	MSV	Handball	6950	140	Final
2110/12	December	28	28:00	Calgary	Winter Olympics	Winter	7000	141	Final
2111/04	April	5	5:00	Chamonix	Jeux Olympiques	Winter	7050	142	Final
2112/07	July	12	12:00	Los Angeles	Summer Olympics	Summer	7100	143	Final
2113/10	October	20	20:00	Chamonix	Jeux Olympiques	Winter	7150	144	Final
2114/01	January	30	30:00	Calgary	Winter Olympics	Winter	7200	145	Final
2115/05	May	10	10:00	Los Angeles	Summer Olympics	Summer	7250	146	Final
2116/08	August	20	20:00	Los Angeles	Summer Olympics	Summer	7300	147	Final
2117/11	November	30	30:00	Calgary	Winter Olympics	Winter	7350	148	Final
2118/03	March	10	10:00	Chamonix	Jeux Olympiques	Winter	7400	149	Final
2119/06	June	18	18:00	Los Angeles	Summer Olympics	Summer	7450	150	Final
2120/09	September	22	22:00</						



Table 4. Source material chemistry by INAA and magnetic susceptibility.

Sample	Ag	As	Au	Ba	Bi	Br	Ca	Cl	Co	Cr	Cu	Fe	Hf	Mn	Nb	Ni	Pb	Rb	Sr	Ta	Ti	U	V	Zn	Zr	
Concentration	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	
GRI01	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI02	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI03	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI04	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI05	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI06	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI07	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI08	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI09	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI10	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI11	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI12	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI13	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI14	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI15	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI16	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI17	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI18	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI19	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI20	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI21	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI22	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI23	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI24	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI25	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI26	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI27	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI28	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI29	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI30	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI31	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI32	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI33	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI34	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI35	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30

Sample	Ag	As	Au	Ba	Bi	Br	Ca	Cl	Co	Cr	Cu	Fe	Hf	Mn	Nb	Ni	Pb	Rb	Sr	Ta	Ti	U	V	Zn	Zr	
Concentration	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	
GRI01	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI02	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI03	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI04	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI05	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI06	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI07	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI08	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI09	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI10	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI11	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI12	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI13	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI14	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI15	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI16	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI17	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI18	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI19	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI20	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI21	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI22	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI23	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI24	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI25	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5	0.5	4	30
GRI26	4.5	9	45	500	1	1	1	10	3	0.1	1	1	1	5	500	100	20	0.2	0.1	5	500	1	0.5			



Table 5. Magnetic susceptibility and general petrographic content of Coombs site ceramic sherds.

Tradition	Series	Cross	Fig Number	Weight Grams	Magnetic Susceptibility S Units	Magnetic Susceptibility Per Gram (G/G)	Quartz	Feldspar	BF	SP	Enstat	VSF	Mica	MBF	Glass	Potassium	Amphibole	Magnetite	
Tusayan Grey Ware	Almond/Concealed	1197/131*	5.41	0.06	0.0111		XX	X										X	
		1060/464	7.34	1.96	0.2476													X	
		792/24	7.19	0.19	0.0264	XX	X											X	
		916/142	5.38	1.01	0.1877	XX	X	X	X	X	X							X	
		927/23	5.47	0.14	0.0256	XX	X											X	
		927/24	3.34	0.03	0.0099	XX													X
		676/84*	3.29	0.23	0.0624	X	XX												X
		676/135	9.91	0.83	0.0838														X
		688/101	8.44	0.47	0.0557														X
		723/113	7.12	1.17	0.1648	X	X												XX
Tusayan Concealed	Almond/Concealed	676/110	6.11	0.54	0.0874	X	X											XX	
		549/114	1.86	0.37	0.1969	X	X											XX	
		563/14*	7.23	0.61	0.0841													X	
		1223/23	3.77	0.07	0.0121	XX	X											X	
		1263/10	5.01	0.51	0.1018	XX	X	X	XX									X	
		1246/206	3.76	0.32	0.0851														X
		1220/20	4.92	0.04	0.0093	XX													X
		1723/1142*	12.90	1.68	0.1223	X	X												X
		1413/15	4.54	1.02	0.2247	X	X												X
		779/53	3.07	0.20	0.0631														X
Tusayan Concealed	Almond/Concealed	776/99	3.18	0.26	0.0818	X	X											X	
		770/104	3.36	0.70	0.2083	X	X											X	
		775/23	2.17	0.23	0.1182	X	X											X	
		335/189*	9.81	1.35	0.1274	X	XX												X
		113/2	7.40	0.33	0.0716	X													X
		81/26	6.30	0.36	0.0564														X
		214	3.43	0.31	0.0571														X
		1149*	6.92	0.65	0.1074	X													X
		214/41	7.15	1.38	0.1920	X	X												X
		452P	2.12	0.30	0.1288	X													X
Virgin North Creek Concealed	Almond/Concealed	113/32*	4.92	0.34	0.0897	XX	XX											X	
		194/13*	16.33	1.83	0.0907	XX	XX											X	
		4852	5.83	0.37	0.1017	XX	X	X	X	X	X							X	
		214/232*	3.92	0.07	0.0118	XX	XX											X	
		768/567	7.89	0.60	0.0760	XX	XX												X
		768/113	7.53	0.73	0.1010	XX	XX												X
		733/436	4.31	0.29	0.0672	XX	XX												X
		1268/83*	3.66	0.17	0.0300	XX	XX												X
		1274/62	4.72	0.38	0.0802	XX	XX												X
		769/1269	3.11	0.24	0.0772	XX	XX												X
"Grey Ware," rock tempered	Almond/Concealed	768/970	3.06	0.18	0.0588	XX	XX												X
		864/14*	5.60	1.03	0.1304	XX													X
		1160/18	6.89	2.84	0.3195	XX	X												X
		4087	7.11	0.43	0.0603	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		1307/67	4.65	0.49	0.1034	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		1360/13	5.23	0.48	0.0914	X	X	XX											X
		1367/77	3.75	0.30	0.1111	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		1164/491*	11.62	0.50	0.0608	XX	X												X
		932/154	8.67	0.06	0.0069	XX	X												X
		1744/23	5.52	0.06	0.0109														X
Johnson Concealed	Almond/Concealed	769/599	4.84	0.73	0.1508	XX													X
		1128/407	4.34	0.19	0.0418	XX	X												X
		1778/24	3.84	0.06	0.0076	XX	X												X
		778/24	3.84	0.06	0.0076	XX	X												X
		504/136*	5.71	0.27	0.0473														X
		214/5	3.43	0.31	0.0904	X													X
		214/64	2.73	0.20	0.0727	XX	X												X
		19/688	1.37	0.08	0.0584	X	X												X
		30/20*	3.23	0.42	0.0803	X	XX	XX											X
		319/33	6.47	0.21	0.0327														X
"Grey Ware," cracked rock and shell	Almond/Concealed	220/120	6.18	0.17	0.0275														X
		219/130	7.21	0.05	0.0068	XX	X												X
		1504/413	4.24	0.15	0.0445	XX	XX												X
		478	3.09	0.34	0.1748	X	X	XX											X
		413/462	3.03	2.24	0.7393	X	X	XX											X
		1145/131*	6.94	0.43	0.0645														X
		1340/132	3.78	0.37	0.1308	XX	X												X
		1170/28	4.69	0.34	0.0935														X
		849/11	6.92	0.71	0.1170	XX	X												X
		953/29	3.47	0.33	0.1002														X
Black Mesa E/W	Almond/Concealed	1100/10*	6.79	0.16	0.0226	XX	X	X	XX										X
		563/121*	8.73	0.80	0.0916	X	X												X
		633/118	10.81	1.92	0.1776	X	X	XX											X
		805/100	6.40	0.40	0.0455	XX	X	XX											X
		1181/92	5.43	0.41	0.0792	X	X	XX											X
		864/70	3.22	0.06	0.0048	XX	XX	XX											X
		1367/951*	7.44	0.05	0.0063														X
		1013/18	4.88	0.06	0.0122	X	X	X	XX										X
		1066/209	3.89	0.27	0.0894	X	X												X
		1109/227	2.30	0.02	0.0027	XX	XX												X
Diagnose E/W	Almond/Concealed	788/1214	2.10	0.28	0.1332	XX	XX												X
		1423/118*	3.47	0.39	0.1079	XX	X	X	X										X
		1360/248	3.45	0.25	0.0725	X	XX	XX											X
		1360/242	2.26	0.29	0.0551	X	XX	XX											X
		1100/10*	4.03	0.11	0.0273	X	XX	XX											X
		1107/86	3.25	0.03	0.0154														X
		1231/17	4.11	0.03	0.0073	XX	X	X											X
		801/82	2.82	0.04	0.0133	XX	X	XX											X
		940/113	2.67	0.01	0.0035	X	X	XX											X
		953/69	1.31	0.02	0.0132	X	X	XX											X
Wapiti E/W	Almond/Concealed	1042/112*	5.87	0.44	0.0992	X	XX	X											X
		634/468	4.12	0.03	0.0073														X
		959/1	1.62	0.01	0.0063	XX	X	X											X
		1131/3	4.70	0.21	0.0447	XX	XX												X
		753/543	8.45	0.10	0.0116	X	X	X											X
		1126/228	3.18	0.24	0.2502														X
		1182/18	4.92	0.10	0.0200	XX	X	X											X
		692/26	3.92	0.13	0.0332	XX	XX	X											X
		4442/13*	3.11	0.19	0.0372	XX	XX												X
		Black Mesa White Ware	Almond/Concealed	779/141	3.04	0.03	0.0147	X	XX										
1098/133	4.93			0.07	0.0174	XX	XX												X
656/453	2.30			0.18	0.0466	XX	X	X											X
1355/3*	7.22			0.03	0.0486	X	XX	XX											X
1747/90	8.24			0.10	0.0180	X	XX	XX											X
1656/11	4.96			0.04	0.0081	XX	X	X											X
16/62	11.98			0.58	0.0092	XX	X	X											X
844/4184*	9.21			0.26	0.0291	XX	X												X
Unid/1																			X



Table 5. Magnetic susceptibility and general petrographic content of Coombs site ceramic sherds (continued).

Tractite	Series	Class	TS Number	Weight Grams	Magnetic Susceptibility	Magnetic Susceptibility Per Gram (1/Gram)	Quartz	Feldspar	BF	SP	Scaph	VEF	Mica	MSF	Grog	Pyroxene	Amphibole	Magnetite
San Juan	Padra S/W		1542/8*	10.14	0.10	0.0099	x	x	x									
White Ware			107/14	7.07	0.16	0.0211	x	x	x									
			1040/105	6.00	0.05	0.0083	x	x	x									
			119/157	6.97	0.06	0.0086	x	x	x									
			960/77	6.40	0.12	0.0188	x	x	x									
Chile	Purco	Gallup	1700/20*	7.96	0.37	0.0340	x	xx	xx	x								
White Ware			291/31	27.77	1.47	0.15	xx	x	x									
			287/10	8.19	0.15	0.0183	x	x	x									
			534/44*	3.89	0.06	0.0102	x	xx	xx									
			223/1	27.77	1.47	0.2030	x	x	xx	xx								
			Escudo S/W	1472/25*	6.43	0.09	0.1524	x	xx	xx								
			636/462	7.17	0.11	0.0153	xx	x	x	xx								
			61/222	1.13	0.09	0.0736	x	x	x									
San Juan	Life		Deodaca R/R	764/160*	3.86	0.12	0.0205	xx	x	xx								
Red Ware	Colombia		766/1100	11.99	0.48	0.0400	x	xx	x									
			221/281*	6.33	0.46	0.0552	xx	x	x									
			214/132*	3.02	0.01	0.0033	xx	x	x									
			982/34	3.56	0.15	0.0421	xx	x	xx	xx								
			770/15	4.17	0.10	0.0240	xx	x	x									
			1017/7	3.19	0.16	0.0302	xx	x	x	x								
			1098/149	4.76	1.07	0.2248	xx	x	x	x								
			1109/229	3.93	0.03	0.0099	xx	x	x									
			1013/12*	3.56	0.01	0.0028	xx	x	x	x								
			766/1594	3.47	0.18	0.0319	xx	x	x	xx								
			765/1144	9.96	0.30	0.1583	xx	x	x	xx								
			1000/9	3.53	0.34	0.0963	xx	x	x									
			1152/23	5.12	1.84	0.2109	xx	x	x									
			605/240*	6.10	0.28	0.0459	xx	x	x									
			1227/10	6.09	0.36	0.0445	xx	x	x									
			1080/2*	10.40	0.21	0.0478	xx	x	x									
			463/19	5.40	0.17	0.0315	xx	x	x									
			287/8	6.47	0.13	0.0183	xx	x	x									
			19/215	2.72	0.06	0.0215	xx	x	x									
Tang	Orange		227/282*	6.74	0.09	0.0134	xx	x	x	xx								
Orange Ware			949/53*	8.69	0.87	0.1001	x	x	x	xx								
			502/17*	5.02	0.04	0.0130	xx	x	x									
			376/70	5.57	0.17	0.0315	x	x	x									
			769/846	4.65	0.53	0.1140	xx	x	x									
			1240/235	13.93	0.79	0.0660	x	x	x									
			1381/5	3.44	0.50	0.1433	x	x	x									
			1407/113	5.12	0.09	0.0176	x	x	x									
			1493/100	4.37	0.82	0.1576	xx	x	x									
			801/79	2.92	0.21	0.0719	x	xx	x									
			93/113	1.83	0.17	0.0699	x	xx	x									
			949/46*	3.18	0.45	0.1341	x	x	x									
			1103/103	6.00	0.38	0.1056	x	x	x									
			1043/101	4.03	0.05	0.0124	xx	x	x									
			1465/17	2.86	0.43	0.1349	x	x	x									
			550/51*	11.70	0.12	0.0103	x	x	x									
			726/49	2.09	0.24	0.1154	x	x	x									
			610/90	5.79	1.21	0.2090	xx	x	x									
			655/10	2.49	0.61	0.3450	x	xx	xx									
			219/13*	15.90	0.43	0.0270	xx	x	x									
			696/200	4.43	0.27	0.0609	xx	x	x									
			1176/28	3.51	0.05	0.0142	xx	x	x									
			1558/72	5.08	0.30	0.0294	xx	x	x									
			473/19*	1.36	0.12	0.0892	x	xx	xx									
			1041/7	2.11	0.63	0.2026	x	x	x									
			1145/140	6.97	1.35	0.2188	xx	x	x									
			903/221	5.38	1.19	0.2212	x	xx	xx									
			1248/25	6.47	1.36	0.2102	x	x	x									
			205/15*	4.37	0.07	0.0160	xx	x	x									
			1146/90	3.15	0.09	0.0286	xx	x	x									
			1005/126	3.65	0.39	0.1068	xx	x	x									
			226/23*	4.49	0.38	0.0860	x	x	x									
			1466/5	3.28	0.80	0.2439	xx	x	x									
			1552/19	10.03	1.19	0.1581	x	x	x									
			949/58*	3.97	0.31	0.1044	x	x	x									
			1306/189	5.65	1.12	0.1182	x	x	x									
			770/18	2.92	0.38	0.1118	x	x	x									
			473/63	1.81	0.26	0.1438	xx	x	x									
			649/56	2.80	0.53	0.1993	x	x	x									
			202/24*	11.73	3.91	0.3338	x	x	x									
			1734/6	3.63	0.37	0.1019	x	x	x									
			1587/5	6.63	0.24	0.0573	xx	x	x									
			55/66*	3.63	0.36	0.0992	x	x	x									
			1407/86	19.77	0.91	0.0480	xx	x	x									
			132/2*	3.36	0.39	0.1131	x	x	x									
			429CV	2.03	0.31	0.1325	x	x	x									
			429CV	2.08	0.29	0.1394	x	x	x									
Utah Desert Faint Grey Ware			219/53*	7.31	1.17	0.1623	x	xx	xx									
			1360/182	5.80	1.15	0.1923	x	xx	xx									
			1360/211	3.00	0.88	0.1932	x	xx	xx									
			1360/132	2.09	0.56	0.2674	x	xx	xx									
			429/17	4.29	0.69	0.1608	x	x	x									
Utah Desert Grey White			226/481*	3.17	0.52	0.1540	x	xx	xx									
			226/176	2.37	0.35	0.1542	x	xx	xx									
			460	2.57	0.39	0.1548	xx	xx	xx									
			160	2.56	0.36	0.1606	xx	xx	xx									
			554/4*	7.36	0.73	0.1026	x	x	x									
			1477/4	10.35	0.67	0.0649	x	x	x									
			1178/11	9.50	1.45	0.1706	x	x	x									
			1184/110	4.46	0.60	0.1390	x	x	x									
			1404/68	4.74	0.33	0.0696	x	xx	xx									
			1248/1	3.40	1.07	0.1981	x	x	x									

* Chemistry and full petrography available. x = present, xx = very common or more abundant.

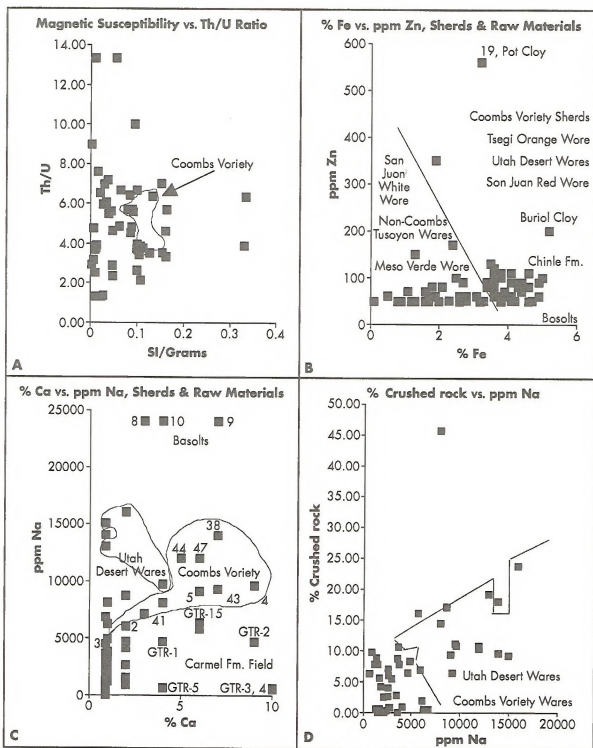


Figure 2. Scattergrams for geochemistry, petrography, and magnetic susceptibility.

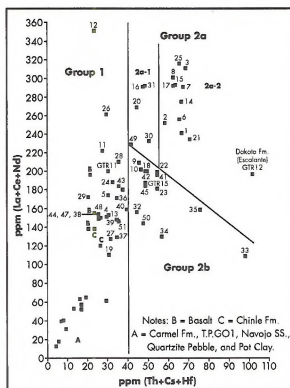


Figure 3. Rb Chemical grouping scattergram.

The quartzite sample has a thorium depleted ratio of 1.00. There are no source samples studied that have excessively high Th/U ratios.

Since the local Coombs site ceramic pottery is a man-made mixture of the fine-grained sediments (paste) that are depleted in thorium, such as the Chinle Formation sediments from the Burr Trail, and a temper that has normal thorium/uranium values (quartz sands and crushed basalt for local Coombs wares), the Coombs variety pottery should plot within the regional source material field. This is true for all but one sample. Sample 3, Tusayan corrugated (Coombs variety) shows excess Th/U values (6.35). This sherd cannot be sourced from only the source samples studied here. Petrographic analysis indicates a basaltic temper that is consistent with local andesine-olivine basalts. Consequently, in order for the Th/U ratio to be in excess, the paste must be from an unidentified source that is thorium enriched over uranium. Coombs variety wares (2, 3, 4, 5, 38, 41, 43, 44, and 47) do, however, plot in a cluster. To the right of that cluster are the Utah Desert gray wares (48, 49, 50), and below the cluster is the Utah Desert white

ware (51). Sample 50, the Utah Desert gray ware (Sevier gray) also has an excess Th/U ratio (5.68). This sample is likely from the Wasatch Plateau on the basis of its temper, which is a crushed trachyandesite vitrifier cap rock (latite) that is very similar to a temper reported by Geib and Lyeis (1993). A total of 22 ceramic sherd samples have excess thorium over uranium values and require some other source material(s) beyond those studied here. These samples are as follows: Tusayan gray ware—1, 3, 6, 7, 8, 10, 14; Tusayan white ware—15, 17, 21, 22, 23; Cibola white ware—27; 29 (probably from the Henry or Abajo Mountains); Tsegi orange ware—45; 40 and 42 (probably from the Henry or Abajo Mountains); San Juan red ware—30, 31, 33; Mesa Verde white ware—25; and Utah Desert gray ware—50 (probably from Wasatch Plateau).

Figure 2B is a scattergram that shows the concentration of Fe vs. Zn for the ceramics and source samples. This scattergram clearly divides the ceramic wares into two main groups. The Coombs variety sherds cluster with the Tsegi orange ware, Utah Desert wares, and San Juan red ware. The source samples that cluster with these wares are basalts, the Chinle Formation samples, the Coombs site burial clay, and the pot clay with the arsenic mineral, realgar. This scattergram provides a simplistic division for the source samples and ceramic ware types that is similar to a large variety of other geochemical scattergrams studied (such as: Th/U vs. (La/Ce)+Lu, Th vs. Fe, U vs. Th, Cr vs. Ce, among others).

Figure 2C is a scattergram for Ca vs. Na concentrations for the ceramics and the source samples. In Figure 2C, the Utah Desert wares and the Coombs variety wares are clearly separated from the other ware types studied. Samples 2 and 3 are Tusayan gray wares (Coombs variety) and they do not fit into the Coombs variety cluster field (their sodium and calcium values are too low). They do behave similarly to other Tusayan gray and white wares. Figure 2C also shows the source samples for the sherd Na vs. Ca distribution. It is clear that the Coombs variety sherd cluster is located between the basalt source samples (8, 9, 10)



and the Carmel Formation, and also the Chinle Formation samples (which are just below Coombs variety sherd sample number 3) and the basalts. This spatial positioning demonstrates the geochemical "line rule" which simply states that a graphic plot for an element or a group of elements of two different source samples and a mixture of those source samples will be related in the following manner: the mixture will plot between the two source samples, and the distance of the mixture from any one source sample will be related to the quantity of that source sample in the mixture. In Figure 2C, Coombs variety ware sample 41 almost falls on a line between the Chinle Formation samples and sample 9 (basalt). The distance from the Chinle Formation to the sherd is shorter than the distance from the basalt to the sherd, therefore there is more paste than temper in the sherd sample. In order for the line rule to be used for compositional calculations, there should be some certainty that the source samples are from the exact same outcrop (or very close to it) as was used for the manufacture of that sherd.

The line rule can also be used to suggest that certain source samples cannot be parents to a ceramic sherd. For example, in Figure 2C, the Carmel Formation clay sample GTR-1 mixed with Carmel Formation temper sand sample GTR-4 cannot be the only source parents for any of the Coombs variety ceramics. The sodium values for the sherds require a basalt composition source material. This is obvious since none of the Coombs variety wares plot between the two Carmel Formation source samples, but do plot between the Carmel Formation samples and the basalts. It is possible to calculate a three-component system that contained clay, quartz sand, and crushed basalt, so that the three components (for example, Carmel Formation 1 and 4, and basalt 9) could form the edges of a triangle. If the Coombs variety sherds plotted inside that triangle, then the source components may be valid. Again, concentrations can be calculated on the basis of the location of the mixture relative to the corners of the triangle. This would work for the Coombs variety sherds. A four-component system would use a rectangle, so that, for

example, the components—grog, quartz sand, basalt, and clay—could be calculated in a ceramic sherd mixture.

In sourcing calculations it is possible to use petrographic parameters combined with geochemical parameters in scattergrams to look at similarities and differences between ware types. Figure 2D uses sodium values in comparison to the amount of crushed rock. Both the Coombs variety wares and the Utah Desert wares plot in a separate field from the rest of the ceramic samples.

Table 2 reports the basic temper contents for all of the ceramic samples studied. There are a large number of samples with igneous, metamorphic, and volcanic tempers that are not represented in the local geologic formations. The Coombs site tempers used as evidenced in the Coombs variety wares are a crushed andesite-olivine basalt from Boulder Mountain, coarse-grained well-rounded quartz sand from the Carmel Formation, and clay from the Chinle Formation. The Moenkopi and Tusayan corrugated (Coombs variety) wares (2, 3) have standard local tempers, but the clay-paste cannot be chemically correlated to the Chinle Formation, Carmel Formation, or any other fine-grained sediments investigated. An additional clay-paste source is needed to support the local manufacture of these sherds.

The San Juan white ware sample (26) has a granodiorite temper, and the San Juan red wares contain granite (30, 32, 33, 34) and diorite (31) as tempers. These acid to acid-intermediate crushed igneous rock-type tempers are not locally available and can be used to characterize the source area(s) for both the San Juan red and white wares. Grog and sedimentary quartz sand are also used in these tempers.

Mesa Verde wares (24, 25) studied contain crushed amphibole-norite, which is a granular basic igneous rock composed mostly of amphibole, pyroxene, and plagioclase (laboradorite), in addition to quartz sand and grog. The quartz and grog concentrations differ more than the crushed rock portion of the temper. This rock-type temper is not locally derived,



but could easily be considered as being sourced from the Colorado-New Mexico area.

Three Cibola white wares were studied (27, 28, 29), all of which contain a porphyritic diorite (hornblende porphyry) that is similar to the rock types in the Henry and Abajo Mountains (Geib and Lyneis, 1993). In addition to this temper, two of the sherds also contain basaltic glass (27, 28) and andesine-basalt (28). The andesine-basalt does not contain any observable olivine, but is still similar to the local Tertiary Boulder Mountain basalts. This temper association is not the same as observed at the Coombs site, but contains materials that are likely of nearby origin, such as in the Abajo or Henry Mountains (porphyritic diorite). These rock types are also present in a variety of other locations, including New Mexico, Colorado, and Arizona. Without a comprehensive petrographic and geochemical library for the Anasazi region during the Dissemination and Classic periods, it is difficult to tie down temper associations to specific localities. Further study of Cibola white wares is certainly indicated as there is that hint based upon these temper associations that there may be local varieties.

Only one Utah Desert white ware sherd (Ivie Creek) was studied, which also has a porphyritic diorite temper (with no other material) that maybe sourced from the Henry or Abajo Mountains. A total of three Utah Desert gray wares were studied, two of which (48, 49) have local andesine-olivine basalt tempers as if they were manufactured at the Coombs site. The third sample (50, Sevier gray) is dominated by a trachyandesite and vitrified glass latite caprock that is likely sourced in the Fremont territory of the Wasatch Plateau (Geib and Lyneis, 1993).

A total of 14 Tusayan gray ware sherds were studied, 4 of which are classified as Coombs variety sherds (2, 3, 4, 5), all of which have classic andesine-olivine basalt tempers. Of the 10 remaining sherds, 2 have crushed rock tempers (11, 14) consisting of an amphibolite (11) and a mixed gabbro and dacite (14), and 3 samples (6, 7, and 8) have andesine-olivine

basalts (sample 8 also contains sedimentary quartz temper). Of the remaining samples, 10 and 13 are tempered with sediment and grog, sample 12 contains grog temper, sample 1 is composed only of sediment temper, and sample 9 contains both sediment sands and crushed sandstone.

A total of nine Tusayan white ware samples were studied, four of which contained crushed rock tempers: sample 15—a porphyritic vogesite which is a lamprophyre; sample 17—a diorite temper; sample 21—both diorite and porphyritic andesite; and sample 22—a white chert cemented sandstone. None of these tempers appear to be locally derived. Only two (18, 21) of the samples studied had observable volcanic ash (see: Geib and Callahn, 1987).

A total of 13 Tsegi orange ware sherds were studied, 5 of which are Coombs variety sherds with classic andesine-olivine basalt tempers. A total of two sherds (40, 42) contain porphyritic diorite (similar to the Henry Mountain material), but their temper composition is more complex. Sample 40, Citadel polychrome contains volcanic ash, quartz sand, and grog, and sample 42, Tsegi red/orange contains a crushed augite-plagioclase-olivine basalt, in addition to quartz sand and grog. Medicine black/white (36) contains crushed diorite and andesite with volcanic ash, quartz sand, and siltstone, and sample 45 (Tsegi orange) also contains crushed diorite with quartz sand and grog. The crushed diorite in these samples is not the same as the crushed porphyritic diorite in samples 40 and 42. Sample 46, Cameron polychrome, also contains a few grains of diorite, but is dominated by grog and quartz sand. The remaining three samples (35, 37, 39) all contain volcanic ash. Sample 35 also has quartz sandstone and a few quartzite clastics. Quartzite clastics were also noted in sample 36. Sample 37, Tusayan black/red contains a few siltstone fragments, and sample 39 contains crushed augite-plagioclase-olivine basalt, which is very similar to sample 42. This basaltic temper (39, 42) is not the same basalt as is found at Boulder Mountain, but may be similar to the basalt outcrops east of Otter Creek and northwest of Boulder, Utah (Geib and Lyneis, 1993: Figure



5, unit Qth). The overall petrography of the Tsegi orange ware is much more complex than any of the other ceramic traditions studied. A general pattern appears to include volcanic materials in the temper. This is true for 11 of the 13 samples. Imported Tsegi orange ware and Coombs variety ware are also quite similar in magnetic susceptibility, which is likely a function of the igneous and volcanic tempers used in these ceramics.

Rare earth, thorium, cesium, and hafnium distributions are studied (Figure 3) in a scattergram as (La+Ce+Nd) vs. (Th+Cs+Hf) to acquire simple clusters for the source materials and the ceramic sherds. The rare earth elements with the highest concentrations (La, Ce, and Nd) were chosen for study. The utilization of these elements and thorium + cesium + hafnium is based upon the concept that the geologic distribution of these elements is dominantly a function of the source material. These elements also show major variations in their distribution in acid rocks and basic rocks. Thus, we do not anticipate any significant or measurable diagenetic effects relative to these elements. We attribute any major differences in concentration in the sherds to differences in the source rock concentrations, transportation and depositional environments for sediments, and of course, the acid or mafic mineral content of the source materials themselves. Simply stated, basalts and basaltic glass should be quite different than rhyolites, granites, or obsidian. All of the samples studied cluster within three fundamental areas; one of these could be further subdivided. These areas are chemical cluster groups that are referred to as simply REE chemical groups: 1, 2a-1, 2a-2, and 2b. Table 6 summarizes the ceramic chemical group data with temper type and ware type.

Utilizing Figure 2A data, magnetic susceptibility vs. Th/U ratio, ceramic sherds that have significant excess thorium, and therefore are represented by an unknown paste (and, in cases, temper) source fall into the following chemical groups: group 1—2 Cibola white ware sherds (27, 29); group 2a-1—2 San Juan red ware sherds (30, 31); group 2a-2—10 sherds in total: 1 Mesa Verde white ware sherd

(25), 3 Tusayan white ware sherds (15, 17, 21), and 6 Tusayan gray ware sherds (1, 3, 6, 7, 8, 14); group 2b—5 sherds in total: 1 San Juan red ware sherd (33), 2 Tusayan white ware sherds (22, 23), 1 Utah Desert gray ware sherd (50), 3 Tsegi orange ware sherds (40, 42, 45), and 1 Tusayan gray ware (10).

If the line rule is applied to Figure 3, the following samples require additional parent(s) source material beyond those studied here: Tusayan gray ware (1, 2, 3, 6, 7, 8, 12, 14); Tusayan white ware (15, 16, 17, 20, 21); Mesa Verde ware (25); San Juan white ware (26); San Juan red ware (30, 31, 33); and Utah Desert gray ware (49).

Discussion

A total of 16 of the 51 ceramic sherd samples investigated can be attributed to a mixture of the temper and clay source samples studied (Table 6). A total of 35 sherd samples do not either fit into a standard mixing cell using the line rule or do not contain the appropriate elemental concentrations or temper content to be sourced from only the raw materials studied here. Of the 35 samples that are comprised of unknown source material, two are attributed to Coombs variety wares and both of these are Tusayan gray wares, Moenkopi and Tusayan corrugated (Coombs variety). At present these sherds appear chemically to be source from local clay materials that have not been identified. Out of 14 of the Tusayan gray wares studied, only 4 were possibly sourced with the raw materials (Coombs variety ware samples 4 and 5, 9 and 13). Of the nine Tusayan white wares studied, only two were potentially sourced with the raw materials studied (18, 19). One Mesa Verde ware (24) and one Utah Desert gray ware (48) could be tied into the raw materials studied. Of the 13 Tsegi orange ware ceramic samples studied, a total of 9 can be associated with the raw materials studied, 5 of which are Coombs variety wares (38, 41, 43, 44, and 47). The ability to provide chemical correlation between the raw materials and a ceramic sherd does not provide positive

**Table 6.** Ware type temper type, rare earth chemical group, Th/U excess, REE—Line Rule applied, and local

Lab No.	Tradition	Series	Class [note]	REF Chemical Group	Dominant Temper Type					REE Applied Line Rule	Non Local Temper	Possible Neotry Source *
					Basalt	RF	VLF	Srf	Grog			
4	Tusayan Gray Ware	Tagai	Coombs Gray	1	X							X
5	Tusayan Gray Ware	Tagai	Coombs Gray polished	1	X							X
11	Tusayan Gray Ware	Virgin	Gray Ware, rock temper	1		X			X		X	
12	Tusayan Gray Ware	Johnson	Johnson Comagated	1					X	X		
13	Tusayan Gray Ware	Johnson	Gray Ware, sand and sherd	1					X	X		X
15	Tusayan White Ware	Keyenta	Daguerre B/W	1			X					X
24	Mesa Verde White Ware		McElmo B/W	1		X			X		X	
26	San Juan White Ware		Padre B/W	1				X	X		X	
27	Cibola White Ware	Puerco	Goliup B/W [Temper-Henry Mts.]	1		X	X			X		X
28	Cibola White Ware	Puerco	Escanado B/W [Temper-Henry Mts.]	1	X	X	X					X
29	Cibola White Ware	Puerco	Puerco B/W [Temper-Henry Mts.]	1					X			
36	Tegai Orange Ware		Madison B/R	1		X	X		X		X	
37	Tegai Orange Ware		Tusayan B/R	1				X				X
38	Tegai Orange Ware		Tusayan B/R [Coombs Variety]	1	X							X
39	Tegai Orange Ware		Tusayan Polychrome	1	X		X		X	X		
40	Tegai Orange Ware		Chadai Polychrome [Temper-Henry Mts.]	1	X	X		X	X	X	X	
43	Tegai Orange Ware		Tagai R/O [Coombs Variety]	1	X							X
44	Tegai Orange Ware		Tegai Orange [Coombs Variety]	1	X				X	X		X
46	Tegai Orange Ware		Common Polychrome	1					X	X		X
47	Tegai Orange Ware		Common Polychrome [Coombs Variety]	1	X		X		X			X
48	Utah Desert Gray Ware	Fremont	Emery Gray	1	X							X
51	Utah Desert White Ware	Fremont	Kite Creek [Temper-Henry Mts.]	1		X					X	
16	Tusayan White Ware	Keyenta	Black Mesa B/W	2a-1			X	X			X	
20	Tusayan White Ware	Keyenta	Flagstaff B/W	2a-1		X			X		X	
30	San Juan Red Ware	Little Colorado	Duckhorn B/R	2a-1	X	X			X	X	X	
31	San Juan Red Ware	Little Colorado	Middleton Red	2a-1	X			X	X	X	X	
49	Utah Desert Gray Ware	Fremont	Emery Isolated	2a-1	X							
1	Tusayan Gray Ware	Tagai	Montezuma Comagated	2a-2					X	X	X	
2	Tusayan Gray Ware	Tagai	Montezuma Comagated [Coombs Variety]	2a-2	X					X	X	
3	Tusayan Gray Ware	Tagai	Tusayan Comagated [Coombs Variety]	2a-2	X					X	X	
6	Tusayan Gray Ware	Tagai	Gray ally	2a-2	X					X	X	
7	Tusayan Gray Ware	Tagai	Tusayan Comagated	2a-2	X					X	X	
8	Tusayan Gray Ware	Tagai	Kite Slat Gray	2a-2	X				X	X	X	
14	Tusayan Gray Ware	Johnson	Gray Ware, crushed rock and sherd	2a-2		X	X		X	X	X	X
15	Tusayan White Ware	Keyenta	Gardfield B/W	2a-2			X			X	X	X
17	Tusayan White Ware	Keyenta	Black Mesa B/W	2a-2	X					X	X	X
21	Tusayan White Ware	Keyenta	Wapiti B/W	2a-2	X	X			X	X	X	X
25	Mesa Verde White Ware		Unidentified	2a-2	X			X		X	X	
9	Tusayan Gray Ware	Virgin	North Creek Comagated	2b			X	X				X
10	Tusayan Gray Ware	Virgin	North Creek Fugitive Red	2b				X	X	X		
18	Tusayan White Ware	Keyenta	Sage B/W	2b	X			X	X		X	X
22	Tusayan White Ware	Keyenta	Tusayan White Ware	2b		X		X	X	X	X	
23	Tusayan White Ware	Keyenta	Shore B/W	2b			X		X	X		
32	San Juan Red Ware	Little Colorado	Middleton Red	2b	X			X	X	X	X	
33	San Juan Red Ware	Little Colorado	Middleton B/R	2b	X			X	X	X	X	
34	San Juan Red Ware	Little Colorado	Middleton Polychrome	2b	X	X	X		X	X	X	
35	Tegai Orange Ware		Unidentified Tegai Orange Ware	2b			X	X	X			X
41	Tegai Orange Ware		Chadai Polychrome [Coombs Variety]	2b	X			X	X			X
42	Tegai Orange Ware		Tagai R/O [Temper-Henry Mts.]	2b	X	X		X	X	X	X	
45	Tegai Orange Ware		Tagai Orange	2b	X			X	X	X	X	
50	Utah Desert Gray Ware	Great Salt Lake	Senior Gray [Temper-Wasatch Plateau]	2b		X					X	X

Note: Henry Mountain temper is dominated by porphyritic dolomite. This is also present in the Abajo Mountains and possibly other unknown sources.

Note: For the Cibola white wares, the porphyritic dolomite is combined with basalt and basaltic glass (sideromelane) for two of the samples (27 & 28).

Note: Sample 50 has a trachyandesite and vitric VLF (elte caprock temper that probably is sourced from the Wasatch Plateau).

Note: Both Mesa Verde wares (24, 25) are tempered with coralline, quartz sand, and grog. This rock type is definitely not from a local source.

Note: The San Juan and ware samples (20-24) contain calc igneous rock tempers (mostly granite), and one sample has a dolomite (porphyritic); these are not local.

Note: The following samples have tempers that are not likely to be local: 11 - ophiolite; 14 - gabbro and diorite; 15 - porphyritic vesicite (or lamprophyre);

17-diorite; 20-diorite; 21-porphritic andesite and diorite; 22-4e white chert cement in the sandstone is not local; 36-diorite and andesite; 45-diorite;

* The source samples studied here are considered, in a general sense, local with the exception of the Dakota sandstone sample GTR-11.

criteria to assign a known source without a strong positive indication from petrographic analysis. Thus, only the Coombs variety sherds appear to be actually associated with the immediate Coombs site. The other sherds appear to have similar paste-clay sources.

Table 6 provides a summary for most of the chemical and, in general, petrographic data obtained in this study. The REE chemical

groups (three rare earth elements and thorium, cesium, and hafnium) appear to be quite beneficial in distinguishing trade ware and local (regional) pottery. There are a total of 22 samples in chemical group 1, of which 9 appear to be trade ware; 5 appear to be sourced from the nearby Henry or further Abajo Mountains. There are no samples in the 2a group (2a-1, 2a-2) that appear to be made from local source materials. There are 13



samples in chemical group 2b, of which 4 appear to be made from local materials (one is a Coombs variety ware). The fact that Coombs variety wares are found in three of the four REE chemical group categories indicates that the manufacture formula for local pottery production is variable. The bulk of the Coombs production (based upon one sample per class) appears to be in REE chemical group 1, one sample in group 2b, and two samples in group 2a-2.

In this study we have provided an initial petrographic and geochemical survey of some local and regional source materials and a variety of ceramics. The ceramics studied are both trade ware and from local sites, including the Coombs site. Coombs site ceramics appear to be characteristically high in magnetic susceptibility values as a function of the ubiquitous use of local andesine-olivine basalt temper. Some of the trade ware is also high in magnetic susceptibility (especially the Tsegi orange ware) due to other volcanic and igneous rock temper used. Petrographic analysis suggests that there are several sherds that have crushed rock tempers that could be from the Henry or Abajo Mountains, and one sherd that is likely from the Wasatch Plateau based upon its temper.

Mesa Verde ware has distinctively different temper characteristics than any local wares, but one sample (McElmo black/white, 24) may use a similar paste, as the overall chemistry is not that different. It shows a normal Th/U ratio and fits within the line rule for sourcing, yet there is no chemical data on the rock fragment temper—a norite which comprises between about 9 and 10 percent of the sample. There is a quartz sand temper and grog also present. The other Mesa Verde sample studied (25) is chemically very different from the local wares, and has a somewhat similar petrography to the McElmo black/white sample, including a crushed norite temper (about 6 percent) and grog and quartz sand. Both samples have a reasonable concentration of mica (about 1.5 to 3.5 percent). Sample 24 has a lot more quartz temper than sample 25. It appears that much of the chemical signal for the McElmo black/white sample is a function

of the sedimentary source material in the temper and the paste.

The Kayenta core intrusives, such as the Tsegi orange wares (Table 6), appear to be constructed of chemically similar source clays, as observed in the local Coombs (variety) site wares, namely the Chinle Formation. The Tsegi orange ware tempers are somewhat more complex and can be used to distinguish Coombs variety wares from other Kayenta core area production. The similarity of the clay source between the Coombs variety and the Tsegi orange wares in general appears to be even more compelling an argument when the natural distribution of Chinle Formation clays is considered, assuming they are the dominant paste source material for both the local Coombs variety wares and the Kayenta core ceramic production. In effect, this may also be a reasonable argument for some of the Mesa Verde ware samples.

For the most part, there is not much evidence in our limited sampling to ascertain the sources for most of the Tusayan gray and white wares (chemical groups 2a and 2b). Many of the geochemical characteristics of at least the gray wares are very distinctive (significant excess in thorium values).

The best guesswork at present, based upon both the geochemistry and the petrography, places the Coombs variety wares, REE chemical group 1, within a line rule sourcing triangle of Carmel quartz temper, Chinle Formation clay paste, and Boulder Mountain Tertiary andesine-olivine basalt. Lag clays associated with local weathering may not be ruled out as local source materials, as there is insufficient chemical and petrographic data collection on these samples. These may be important with respect to REE chemical groups 1, 2b, and even 2a-2 if there is a significant thorium enrichment in these clays. In the future, with a large base of source material geochemistry, magnetics, and petrography, the more detailed data collection tables presented here can be used to better define individual sources and the ceramics made from them.



Conclusions

This study represents an initial survey of local Coombs variety wares, trade ware, and a variety of potential source samples for temper and paste. All of our conclusions admit to modification as additional field and laboratory data are collected.

The combination of petrographic and magnetic susceptibility data collected provides a compelling means to acquire finite data concerning the differences of Coombs variety wares and associated trade ware. There are strong geochemical characteristics for better defining the trade core production for Kayenta, Virgin, and Mesa Verde wares; and there is a potential for better defining the ceramic core production for the Fremont and Sevier Fremont cultures. The geochemical similarities of the ceramic pottery for Tsegi orange ware, and in a general sense, the local source samples studied, strongly suggests that the sedimentary formations such as the Chinle Formation are used both in the Kayenta core area and at the Coombs site. In essence, only differences in the petrographic composition and the magnetic susceptibility of these sherds can be used for source area classification.

There appears to be extremely different geochemical behavior with respect to the Tusayan gray and white wares and the Tsegi orange ware. This is apparently more of a function of a completely different paste-clay source(s) than a difference in tempering, although tempering is more visually recordable. In order to resolve a variety of sourcing issues that are quite obvious, it will be necessary to expand the source sampling beyond that which was accomplished here.

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Anasazi Occupation in the Northeastern Portion of the GSENM

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Located in south-central Utah in the small ranching community of Boulder, along the northeastern boundary of the GSENM (Figure 1), is a 12th century A.D. Pueblo village known as the Coombs site. Two distinct pueblo units, 10 pitstructures, and isolated habitation and storage rooms have been investigated. Based on the ceramic assemblage, the site appears to be predominantly affiliated with the Kayenta Branch of the Anasazi. Architectural forms and other artifact types also suggest a Kayenta connection. Intrusive ceramic wares, as demonstrated by design elements and temper type, indicate contact with neighboring Western Anasazi and Fremont peoples. A small percentage of Mesa Verde and Chaco ceramics suggests contact or trade with those distant centers.

Palynological data suggest an intriguing relationship between the paleoenvironment

ABSTRACT

■ The Coombs site is a 12th century A.D. Pueblo village located along the southern flanks of the Aquarius Plateau at an elevation of 2042 m (6,700 feet). Ceramic artifacts and architecture suggest cultural affiliation with the Kayenta Anasazi. Intrusive ceramic wares indicate contact with neighboring Western Anasazi and Fremont peoples. Data from palynological studies show vegetation changes in the vicinity of the Coombs site during the A.D. 1100's, and may reflect a trend that affected other indigenous groups, ultimately leading to the abandonment of southern Utah. The Coombs site is one of only a small number of sites to be investigated within the GSENM boundaries. To help define and answer questions concerning long-term adaptation in the area by prehistoric populations, regional archaeological surveys of public and private lands need to be initiated. The data can be used to compare and contrast the Coombs site with other prehistoric Pueblo occupations within the Monument.

and human behavior. These data may have far-reaching implications. For instance, the vegetation changes in the vicinity of the Coombs site may reflect a trend that also affected the Fremont and Western Anasazi, which ultimately lead to their abandonment of southern Utah.

Excavated as part of the Glen Canyon Project (Fowler et al., 1959; Jennings, 1966), the Coombs site is one of only a handful to have been investigated to any extent in or near the new Monument. Madsen (1997) indicates the potential for a significant number of archaeological sites within the Monument's boundaries, allowing for investigations concerning the relationship of the Coombs site to the Kayenta core area and Fremont peoples to the north (Berry, 1982; Geib, 1996; Lipe, 1970). Although limited to a single site, this research is relevant to a number of Monument research and management issues.

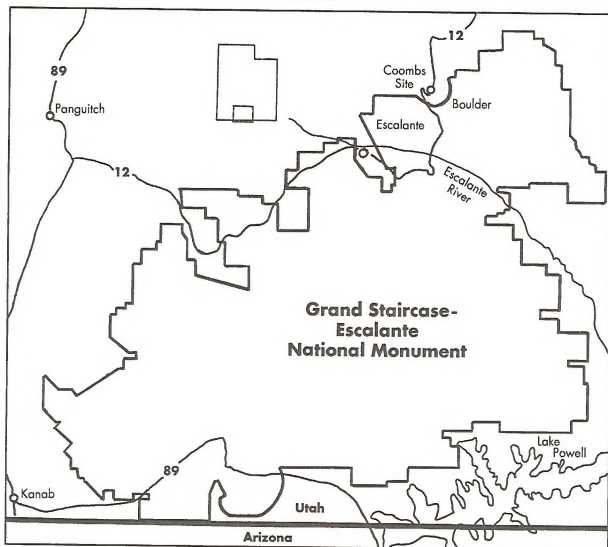


Figure 1. Location of the Coombs site [42GA34] relative to the GSENM.

Location

The Coombs site, 42GA34, is located on the southern slope of the Aquarius Plateau, between Boulder Mountain to the north and the canyons of the Escalante River to the south. The site is on lands administered by the Utah Division of Parks and Recreation. Nearby National Parks include Bryce Canyon, 40 miles to the southwest, and Capitol Reef, 20 miles to the east. The Coombs site is tangent to the GSENM where BLM lands transition to the limits of the town of Boulder in the northeastern portion of the Monument.

Culturally, the site straddles the transition zone between Pueblo peoples to the south and the Fremont to the north, although what

appear to be Kayenta traits are clearly dominant at the site. The sociocultural relationship between the two, not to mention any genetic affinity, remains unclear. As Geib (1996) and Madsen (1997) point out, both quantitative and qualitative surveys and analyses are required to resolve the issue.

Site History

In the late 1880's, settlers in Boulder identified an "Indian Mound" on the north side of town (King, n.d.; LeFevre, 1973), from which they sometimes collected projectile points, metates, manos, and ceramic sherds. Settlers also reported finding "old ditches" they believed were made and used by the prehistoric inhabitants.



Because many families were homesteading in areas near where the ditches led, they simply cleared and reworked the ditches to make them operational once again (LeFevre, 1973). To date, efforts to verify these claims have been unsuccessful.

Scientific investigations were initiated in 1928 when Noel Morss tested the Coombs site. Morss (1931) identified the remnants of several groups of masonry rooms at the top of the low hill, and described three burials found in a sandy drift along the southern slope of the site. He collected a sample of sherds identified as Proto-Kayenta, or what is now called Tusayan ware, concluding that the Coombs site had been occupied by Pueblo (Anasazi) peoples whose material culture resembled that of the Kayenta peoples in northern Arizona.

In 1955, the Coombs site was examined and recorded by James H. Gunnerson as part of a reconnaissance conducted by the Utah Statewide Archaeological Survey for the Department of Anthropology, University of Utah. Extensive excavations began 3 years later as an adjunct to the 1957 Upper Colorado River Basin Archaeological Salvage Project. Under the direction of Dr. Jesse D. Jennings, excavations were conducted in 1958 and 1959. In all, University of Utah excavations identified 77 masonry or jacal rooms, 10 pit-houses, 1 ramada, and 14 burials (Lister, 1959; Lister et al., 1960; Lister and Lister, 1961).

The Coombs site was designated a State Park in 1960 when private lands containing the site were purchased by Garfield County, Boulder City, and the State of Utah. The visitor center was dedicated on July 10, 1970. The site was placed on the National Register of Historic Places on January 1, 1976. Small-scale excavations were conducted by Park staff between 1970 and 1995.

Environment

The Coombs site is located in the geographic center of both Garfield County and south-

central Utah, at an elevation of 6,720 feet (2042 m). Within 10-12 miles north of the site are elevations between 10,000 and 11,000 feet. Traveling that same distance to the south are elevations of only 5,000 feet. The abrupt elevation changes over such a short distance lead to diverse flora and fauna.

The village rests on a well-drained, south-facing alluvial fan (Soil survey field sheets, USDA Soil Conservation Service, 1990). This fan, consisting of eolian sands eroded from the Navajo Sandstone and Carmel Formation, is dissected by West Deer Creek. Mixed into these sand deposits are basalt boulders up to several feet in diameter. Many of these basalt rocks have been used as construction materials in the walls of the village structures. Within the alluvium on which the site is constructed, is a zone of caliche (carbonaceous clay), usually a few feet under the present surface. This material was quarried and used in the mortar mix to cement sandstone and basalt masonry units into place.

West Deer Creek is the primary source of water, a quarter mile to the northeast. Within an 8-mile radius of the site there are six other perennial streams. All of these streams flow generally south, from the Aquarius Plateau into the Escalante River, which passes 10 miles south of Boulder. In addition to a high number of lakes and ponds on the Aquarius Plateau, and the perennial streams that flow off the north, east, and west sides of the mountain, there are enough springs, seeps, and tanks eroded in to the bare, exposed sandstones of the lower, dryer, and warmer country to the south to allow access and utilization of these areas by wildlife and humans. With an average annual precipitation of between 9 and 12 inches, and much more on the Aquarius Plateau, the location was, and still is, well-positioned to take advantage of the water available from the higher elevations by way of irrigation ditches. Summer thunderstorms (monsoons) usually start in July and continue through mid-October. They bring nearly half the annual precipitation, ensuring that summer crops are allowed to finish maturing, and recharge the tanks and waterholes.



The mean annual air temperature is 46 to 49 degrees Fahrenheit. The average number of frost-free days is 120 to 140, making agriculture a viable endeavor (Soil Survey field sheets, USDA Soil Conservation Service, 1990). Maximum temperature extremes are -16 degrees Fahrenheit to +97 degrees Fahrenheit (Doyle Moosman, Boulder National Weather Service reporting station, personal communication, 1991).

Vegetation in the immediate vicinity of the site is a mosaic of pinyon-juniper woodland (*Pinus edulis-Juniperus osteosperma*) and sagebrush scrub (*Artemisia tridentata*). Woodland dominates the rocky outcrops that surround the town of Boulder, as well as more protected localities on the valley floor. Sagebrush, on the other hand, dominates eolian sand sheets such as that which extends east in the lees of the circa 10-m-high hill that marks the Coombs site. Riparian vegetation dominated by willow (*Salix* sp.) lines the water courses. The site itself supports primarily sagebrush scrub, but woodland can be found within 100 m to the north and west of the site.

Site Description

Eighty-seven rooms were identified in the University of Utah's 1958-59 excavation (Lister, 1958, 1959; Lister et al., 1960; Lister and Lister, 1961). Subsequent excavations by Anasazi State Park staff have pushed this number to near 100. Three types of architecture have been identified: jacal, Kayenta masonry, and pitstructures. In addition, one example of a four-post roofed shade, or ramada, occurred on the southern slope of the site (Lister et al., 1960). A minimum of two distinct pueblo units were identified, one L-shaped and one U-shaped, consisting of both habitation and storage rooms. To date, the plaza areas of the two pueblos have not been investigated, other than being dissected by University of Utah test trenches. Ten pitstructures have been excavated on the southern slope of the site. Features within the pitstructures indicate they were likely used for habitation rather than ceremony

(kivas). Estimates suggest only about 50 percent of the site has been investigated.

Site Dates

Table 1 contains published tree-ring and radiocarbon dates. Tree-ring dates indicate a concentration of construction activity during the mid-12th century, although it is possible that construction began as early as the 1120's. The Coombs site remains insufficiently dated to accurately determine the construction sequence, thereby complicating interpretation of how the site relates to the local and regional archaeological context.

Table 1. Tree-ring and radiocarbon dates from the Coombs site (after †Bannister et al., 1969; ‡Marvitt and Fry, 1973; *Daug McFadden, personal communication, 1997).

Structure	Terminal Tree-Ring Date †
Pithouse (F-88)	1165±vv
Pithouse (F-117)	1169±vv
Pithouses	1129v
	1135v
	1142w
	1164±vv
Surface Structure (L-shaped)	1160±B
	1163±vv
Surface Structure (U-shaped)	1159±vv
Unknown Structure	1095±vv*
Unknown Structure	1165±vv*
	Radiocarbon Date ‡
Room 13, Structure A	A.D. 1050±85
Structure Q	A.D. 835±85
Room 9, Structure Q	A.D. 1155±80
Room 2, Structure J	A.D. 1165±80

Artifacts

Ceramics

F. Lister assigned the majority of ceramics at the Coombs site to Kayenta types (Lister, 1959; Lister et al., 1960; F. Lister, 1964). In a letter dated March 1992, J. Richard Ambler (personal communication) states, "A few years ago when passing thru (sic) SLC I took the



time to look at the painted sherds she [Florence Lister] identified as Kayenta, and about 2/3 of them I feel are Virgin, not Kayenta." Ambler does not state on what criteria he bases his argument. Conversely, Geib (1996) believes regional gray ware "is most likely of local production and all part of the same technological and stylistic tradition," questioning the validity of past analyses that categorically separated Fremont, Kayenta, and Western Anasazi ceramics based on raw materials. Geib suggests it may be of greater utility to monitor attributes such as vessel shape, surface finish, and forming techniques irrespective of paste and temper type in order to differentiate sociocultural traditions.

F. Lister states, "Although aesthetic standards were considerably lower, the...pottery manufactured at Coombs could easily be confused with types at home in the Kayenta country were it not for the temper difference" (Lister et al., 1960). It must be noted that the Coombs pottery exhibits a unique type of temper consisting of crushed black basaltic andesite, volcanic glass, white quartz grains, and granules stained with iron oxide. It is often distinct with the naked eye, and even more so under a microscope. F. Lister (Lister et al., 1960) considers the use of crushed igneous rock as temper atypical for Kayenta peoples. Yet, Geib and Callahan (1989) demonstrate the wide use of volcanic tempering agents in the core Kayenta area stating, "A significant proportion of the Tusayan White Ware...contains volcanic ash temper...indicating that the Kayenta potters produced a considerable quantity of this pottery. Volcanic ash seems to have been in common use as a temper by A.D. 1100, and it was perhaps initially used around A.D. 1050." Perhaps the use of volcanic tempering agents at the Coombs site is not so unusual. Further evaluation of this phenomenon would prove interesting, but unfortunately is beyond the scope of this paper (see Morgenstein and Latady, 1998, for additional discussion).

Turquoise

In 1994, 11 samples of turquoise artifacts from the Coombs site were analyzed under a scanning electron microscope. Mineralite grains within each sample were analyzed to determine specific chemistry. Results indicate that all the samples studied were from a single source, dominated by arsenic sulfide and oxide microcrystallites that are generally poor in iron, with some barite present (Morgenstein, 1994). A review of open literature was made to acquire chemical data on turquoise from other western states. A scattergram of the Coombs' samples compared to the control data, measuring for (Fe+Ti) vs. (Ca+K+Mg+Na), is inconclusive. The Coombs' samples all tightly clustered, bearing little relationship to the regional specimens identified through the literature review. In order to carry these studies further, a comprehensive collection of turquoise needs to be made from known localities, and these samples need to be studied by microchemical means.

Shell

It is worth noting that both olivella and bivalve shells are represented in the collection from the Coombs site, indicating established trade relationships with peoples participating in exchange with the west coast (Rafferty, 1990). Only finished items of shell have been recovered, suggesting the receipt of premanufactured shell items, rather than the raw material itself.

Bull Creek Points

Anasazi State Park excavations since 1970 have recovered almost 120 projectiles classified as Bull Creek points, with numerous others recovered during the University of Utah excavations. They exhibit a wide range of variation in form. Generally, these are long, slender, triangular points, although some specimens are short and broad. A defining characteristic is the concave base. Jennings and Sammons-Lohse (1981) describe the base as follows: "The basal concavity varies in depth and in form from a gentle arch to nearly U-shaped. In some instances the concavity is



more linear than curved so that the effect is one of a flat base with tangs extending down." Other characteristics include fine flaking, straight margins and basal thinning. Some specimens closely resemble the specimen that Westfall et al. (1987: figure 6.1, 42WS1632-73) classify as a Cottonwood Triangular. Geib (1996) suggests that long Bull Creek points (exceeding 45mm) are generally found north and west of the Colorado River, while short points (generally less than 40mm) are typically found south and east of the Colorado.

A number of issues need to be addressed:

- 1) Are Bull Creek points a reliable sociocultural indicator and, if so, which social identity is represented?
- 2) A review of the literature shows contradictions in the definition and typing of Bull Creek points versus Cottonwood Triangulars. Length and degree of basal concavity are often defining attributes, but have been applied inconsistently.
- 3) Anomalous with Geib's findings, the majority of Bull Creek points from the Coombs site are of the shorter variety, ranging between 20 and 40mm in length. Of course, if the Coombs villages brought with them strong material culture traditions, the making of shorter Bull Creek points may not be so anomalous.
- 4) Combined with the University of Utah's collection from the site, there are almost 200 Bull Creek points recovered to date. How do we account for this inordinate number of one point type at a single site?

The resolution of the above issues could have significant implications for how we perceive social boundaries.

How we define and type Bull Creek points could affect how we assign cultural affiliation. Are they a Fremont or Kayenta Anasazi phenomenon, or common to both cultures, especially within the transition area defined by Madsen (1989) and Geib (1996), lending

credence to Madsen's suggestion that agricultural peoples in this area might be referred to as "Freaazi" or "Anamont?" At this point, we concur with Madsen's (1989) and Geib's (1996) suggestion that during the Late Prehistoric period a cultural fluidity existed in this transition zone.

Faunal Remains

The faunal assemblage from the Coombs site is varied. Unfortunately, poor provenience control makes specific feature relationships tenuous. Species identified include desert bighorn sheep, mule deer, pronghorn, cotton-tail, jackrabbit, red-tailed hawk, rodent, and bird. Bighorn sheep and mule deer are well-represented by numerous leg and toe bones, indicating entire animals were transported to the site. Interestingly, the majority of long bones exhibit charring and green stick fractures, suggesting marrow extraction (Binford, 1978, 1981; Metcalf and Jones, 1988; Potter, 1995; and Vehik, 1977).

Paleoenvironmental Studies

In 1993 field work was conducted at and near the Coombs site in order to determine the potential of developing a paleoenvironmental record for the Coombs site. Activities consisted of a combination of palynological and packrat midden sampling. Pollen extraction and counting was done by Deborah E. Newman, then of Brigham Young University, while packrat midden analyses were done at Dames & Moore's laboratory in Las Vegas, Nevada.

Pollen Analysis

A geoarchaeological test unit (GTU) was excavated to a depth of 90 cm on the gentle southeast trending slope circa 50 m from the pueblo area. This location was selected because, in the tall sagebrush in the lee of the hill, eolian sand had obviously been accumulating for some time, and therefore sediment accumulation may have been relatively



continuous through the period of occupation of the pueblo.

A total of 18 pollen samples of approximately 200 g of sediment each was collected at 3- to 5-cm intervals from a cleaned face of the GTU, in addition to two surface control samples. Both surface control samples were selected for analysis, as were four subsurface samples. A carbon-rich anthrosol relating to the prehistoric occupation of the site was evident in the stratigraphic profile of the test unit. This stratum became progressively darker with depth until it reached an abrupt, unconformable contact with the underlying, carbon-free eolian sand at 34 cm below ground surface. Four subsurface samples were selected for processing from 14-17 cm, 26-30 cm, 40-45 cm, and 55-60 cm (Figure 2). Considering available tree-ring dates, and accounting for sedimentation rates, the 55-60-cm sample would represent presettlement vegetation, the 40-45-cm sample, just before occupation, the 26-30-cm sample, conditions during occupation or slightly after abandonment, and the 14-17-cm sample, the mid-1600's.

Observing the results from the deepest sample, relatively high percentages of *Artemisia*, *Cheno-ams*, and *Pinus* suggest a mosaic of woodland and sagebrush scrub similar to that which occurs at the site today. The drastic decline in *Artemisia* pollen frequencies with decreasing depth is accompanied by a decline in *Pinus*, and increases in *Compositae* and *Cheno-ams*. We interpret these changes as reflecting a marked reduction of sagebrush scrub and pinyon in the vicinity, and an increase in the abundance of disturbance-adapted species belonging to the *Chenopodiaceae*, *Amaranthaceae*, and *Compositae* (examples include four-wing saltbush, goosefoot, thistle, snakeweed, and rabbitbrush). To appreciate the implied scale of this disturbance, it is worth considering the rather extensive development presently in the vicinity of Boulder that accommodates domestic, agricultural, and other economic pursuits. Despite this, the pollen types that indicate disturbance (and imply, but do not prove ecosystem degradation) are distinctly more common in the prehistoric samples than they are in the modern soil samples.

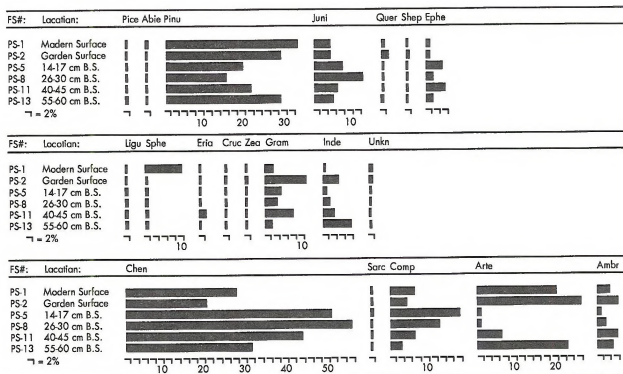


Figure 2. Pollen percentages from the Coombs site, 42GA34 (after Spaulding, 1994).



The changes were either the result of anthropogenic effects on the landscape, including trampling, fuel-wood harvesting, and increased fire frequency, and/or the result of climatic changes. A notable aspect of this preliminary chronology of vegetation change is that it appears to have begun before the apparent time of pueblo construction, and persisted well after Pueblo abandonment. The general absence of evidence for recovery of the local vegetation to preoccupation conditions is striking. This apparent lack of recovery is not unique to the Coombs site. For example, packrat midden evidence from Chaco Canyon indicates that pinyon-juniper woodland was common until circa A.D. 1200 when woodland disappeared, never to return. This vegetation change is attributed to intensive fuel-wood harvesting by a large prehistoric population (Betancourt and Van Devender, 1981). The alternative hypothesis that climatic change was responsible for the reduction of woodland appears less tenable because, in more than 8,000 years, this was the only period when woodland disappeared from Chaco Canyon. Obviously, woodland and sagebrush scrub did recover at the Coombs site, but apparently not until after circa A.D. 1650. Appreciating the limited chronological control that we can apply, the timing of recovery does not appear to match that of known climatic changes in the region.

Packrat Midden Analysis

The magnitude of the vegetation changes implied by the preliminary pollen study from the Coombs site is substantial, but one pollen profile, even if fully developed, cannot adequately address the scale of that vegetation change. Therefore, limited areas of the rimrock in the vicinity of Boulder were subjected to a search for late Holocene packrat middens that might reveal if the woodland of the surrounding hills was also affected. Two packrat (*Neotoma* sp.) middens (designated Bo-1 and Bo-3) were collected from small sandstone rockshelters near the summit of Schoolhouse Ledge, 0.6 km northwest of the Coombs site. Approximately 20 g of packrat fecal pellets from each sample were submitted for

radiocarbon dating. The corrected $\delta^{13}\text{C}$ dates are 260 ± 50 B.P. for Bo-1 and 780 ± 50 B.P. for Bo-3. Dendrochronologically calibrated intercept dates are A.D. 1650 for Bo-1 and A.D. 1260 for Bo-3. Sample Bo-1, therefore, reflects vegetation conditions after abandonment, while Bo-3 reflects conditions during occupation, or shortly after abandonment. Based on the dates, Bo-1 and Bo-3 macrofossil assemblages correlate with the pollen samples from 14-17- and 26-30-cm samples, respectively. Results of the macrofossil analyses are contained in Table 2.

Contrasts between vegetation conditions inferred from the two samples suggest that the local woodland was more diverse at circa A.D. 1260 than it was during the Late Prehistoric period (circa A.D. 1650). Increased diversity in woodland plant communities if often promoted by an opening of the canopy (i.e., reduction in the standing biomass of trees such as pinyon and juniper), and by soil disturbance. This is consistent with the palynological evidence for vegetation change concurrent with pueblo occupation, and the absence of vegetation recovery until the last few centuries. The presence of rice grass and sunflower in the older midden (Bo-3) is intriguing, not only because these species were important in aboriginal subsistence and ceremonial practices (e.g., Whiting, 1939), but also because sunflower is a disturbance-adapted species. Species of *Helianthus* rarely, if ever, occur in habitats that have not been subject to severe disruption of the top soil.

Normally, we would not expect to see such clear evidence of vegetation change arising from a preliminary study involving the analysis of four pollen samples and two packrat middens. Serendipity appears to be the primary cause. The quality of preservation of the fossil pollen from the test unit was excellent, dendrochronological dates were available from the site, there was clear evidence in the stratigraphic column for initiation of intensive human occupation, and the packrat middens collected from Schoolhouse Ledge happened to be of the same approximate age as pollen samples from the test unit selected for



Table 2. Plants from the Boulder-1 and Boulder-3 packrat midden sites (after Spaulding, 1994).

Family	Genus and Species	Bo-1 (veg)	Bo-1 (mdn)	Bo-3 (veg)	Bo-3 (mdn)
	Radiocarbon date	-	230	-	730
	± 1 s.d.	-	50	-	50
	Lab no.: Beto-	-	71014	-	71015
Boraginaceae	<i>Cryptantha</i> sp.	1	2	3	1
Cactaceae	<i>Opuntia</i> sp.	-	3	-	1
Chenopodiaceae	<i>Ceratoides lanata</i>	-	-	-	†
Compositae	<i>Artemisia bigelavii</i> -type	1	-	-	-
	<i>Artemisia nava</i>	1	-	1	-
	<i>Artemisia sec. tridentata</i>	-	2	-	3
	<i>Chrysanthamnus</i> sp.	-	-	-	1
	<i>Haplopappus</i> sp.	1	-	-	-
	<i>Helianthus annuus</i>	-	-	-	2
Cruciferae	<i>Lesquerella kingii</i> -type	-	-	-	2
	gen et sp undetermined	-	†	-	-
Cupressaceae	<i>Juniperus osteosperma</i>	3	4	2	4
Ephedraceae	<i>Ephedra viridis</i>	1	†	2	†
Ericaceae	<i>Arctostaphylos pungens</i>	1	-	-	-
Gromineae	<i>cf. Bouteloua</i> sp.	1	-	-	-
	<i>Oryzopsis hymenoides</i>	-	-	-	3
	Paaceae undet.	2	†	1	-
Pinaceae	<i>Pinus edulis</i>	4	4	3	5
Polygonaceae	<i>Eriogonum fasciculatum</i>	1	1	-	-
	<i>Eriogonum</i> sp.	1	-	-	†
Rosaceae	<i>Amelanchier utahensis</i>	1	3	2	†
	<i>Cercocarpus intricatus</i>	-	2	-	†
	<i>Cawonia mexicana</i>	2	2	2	2
	<i>Purshia tridentata</i>	-	-	-	†
Scrophulariaceae	<i>Penstemon</i> sp.	1	-	-	-
Viscaceae	<i>Arceuthobium</i> sp.	-	1	-	3
	Ni:	15	13	8	17
	Nts:	10	10	6	12

Estimated relative abundance: 5, very abundant; 4, abundant; 3, common; 2, occasional; 1 rare; †, trace (one fragment only); I, opponent extrolocal taxon. Other abbreviations: N, number of plant taxa; Nts, number of tree, shrub, and succulent taxa; mdn, species encountered in the microfossil assemblages; veg, species encountered in the census of the present vegetation

analysis. Another reason for the clarity of these data, particularly the pollen data, is the apparent magnitude of vegetation change. Environmental degradation is an apt description of its severity, and climatic change cannot easily be invoked to account for it.

Despite the apparent magnitude of the vegetation change at the Coombs site, and its implications for understanding the archaeology of this and other nearby sites, a caution arising from our small sample size is in order. It is possible that the analysis of more samples

from the test unit would reveal highly variable pollen frequencies, indicating that the cause of these apparent changes was due to sedimentological effects and differential pollen deposition, and not vegetation change. Similarly, two packrat middens are hardly sufficient to characterize the history of woodland on the rimrock of the area over the last circa 800 years. Nevertheless, considering the resources available for this study, the results exceeded our expectations.

The above-referenced data is also interesting in light of interpretation offered by Berry (1982) and Lipe (1970). Lipe refers to a general southward retreat of Kayenta peoples about A.D. 1150 due to changing climatic conditions, and finds the Coombs site atypical for Kayenta peoples during this period. He offers some characteristics that may help explain the site's presence. For example, it is well-favored ecologically, being in a high valley with abundant good soil and permanent streams small enough for easy diversion. It is also on the extreme northwest frontier of the Kayenta Branch and is one

of the few sites with evidence for continuing contact between Anasazi and Fremont peoples. Berry contends that widespread abandonment of Colorado Plateau sites during periodic Plateauwide droughts resulted in the establishment of high-elevation refugia, the Coombs site possibly being one of these. The issue bears additional consideration in light of Lipe's observations, Berry's contentions, and the limited paleoenvironmental data presented here.



Local Archaeology

A literature survey, as well as local knowledge, testifies to the existence of numerous sites around Boulder and along the surrounding drainages. Many of these sites comprise lithic scatters and campsites (Tipps, 1988), although sites with identifiable masonry and subsurface structures are known. Based primarily on ceramics, some of these sites in the immediate vicinity are clearly associated with the Coombs site. Other sites are likely contemporary with Coombs, but probably not a direct result of the villagers' activities. Projectile points, rock art, and data from a limited number of excavations in the area represent a spectrum of activities, time periods, and cultures.

One-half mile west of the Coombs site is Boulder Creek. Along this perennial stream are several field houses associated with Coombs variety ceramics. A number of small sites along Boulder Creek evidence rock-lined hearths, groundstone, and copious lithic debitage. This holds true for many of the primary drainages coming off the Aquarius Plateau. Rock art from the surrounding area clearly demonstrates the presence of Archaic and Fremont peoples; classic Anasazi design elements are nondescript or simply nonexistent.

Discussion

Environmental Studies

Both the pollen and packrat midden analyses indicate significant vegetation changes occurred near or during occupation of the village. The question is whether the changes are a result of climatic shifts, human impact, or both. As discussed above, because of the pollen types involved, human activities appear to be implicated at least in part, and the magnitude of the vegetation change appears to have been substantial. The need for additional control units on- and off-site, and from surrounding sites, is apparent. Additional packrat midden samples could easily be obtained from

the surrounding Navajo Sandstone outcroppings for further analysis. Similar and stratigraphically more comprehensive testing in the Monument would refine our understanding of regional paleoenvironmental changes. In this regard, we note that the placement of test units for paleoenvironmental studies needs to be carefully considered relative to their proximity to pueblos that were the focus of intense human activity.

Site Dating

Although enough tree-ring and radiocarbon dates exist from the site to provide gross occupation dates, additional dates are required to clarify site chronology. Initial occupation, construction sequence, and abandonment dates will help define how the Coombs site fits within local and regional contexts, that is, assuming there are sufficient dates from other area sites. Clearly, Madsen's (1997) recommendation for a broad and detailed assessment of Monument archaeological resources is warranted prior to any wholesale public consumption of the Monument.

Geib's (1996) suggestion that boundary dissolution between the Fremont and Anasazi occurred after A.D. 1000 could be addressed by a more refined chronology at the Coombs site and additional dates from surrounding Fremont sites (Jacklin, 1988).

Kayenta Access

Geib (1996) puts it succinctly when he questions why an established Fremont population would permit a migrant Kayenta group to establish and occupy a substantial village. Through extensive surveys of the Monument boundaries, it would be interesting to determine if there was an established corridor of Kayenta sites, or if the majority of archaeology within the Monument reflects a Kayenta/Fremont social continuum. As Madsen (1997) points out, only 8,509 site numbers have been issued for Garfield and Kane Counties combined. He estimates there may be more than 100,000 sites within the Monument, leaving ample room for cultural and chronological refinement.



Collections and Archives Storage

Lastly, though not directly related to the Coomb site specifically, is the issue of storage for collections and data from the Monument. Given the likelihood for extensive archaeological investigation, it is prudent to establish a central repository. The cautionary tale is the result of the Glen Canyon Project where collections have been split between multiple institutions in different states. The result is a loss of archaeological integrity, differential management of the collections, and a general inconvenience for researchers.

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Archaeology in the Grand Staircase-Escalante National Monument: Research Prospects and Management Issues

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Archaeological sites in the western United States are being damaged and destroyed at an unprecedented rate, not only by development, but also by looters, vandals, casual collectors, and an interested and curious public loving the sites to death. One of the reasons President Clinton established the Grand Staircase-Escalante National Monument was to preserve the numerous and diverse array of archaeological sites in a relatively unspoiled tract of land in southern Utah. By establishing the Monument, he protected these sites for public appreciation and enjoyment for generations to come. President Clinton also recognized that sites in the Monument have outstanding research potential and encouraged their scientific study. These goals of preservation and study are complimentary because ongoing research is essential to generating information for public interpretation and helping visitors share in and appreciate the Monument's past.

In this paper, I discuss these two themes—scientific research and site preservation. First I summarize some past archaeological studies as examples of the kind of research that has been done in the Monument. I also touch on some

ABSTRACT

■ Preserving, protecting, and encouraging the scientific study of archaeological sites over a large area were among the important reasons for establishing the Grand Staircase-Escalante National Monument. Previous archaeological research in and around the Monument is not extensive, but shows that sites in the Monument have vast research potential and are well-suited to addressing a multitude of scientific research problems. This paper identifies examples of this research potential, with an emphasis on hunter-gatherer archaeology before and during the arrival of agriculture. In addition, scientific data needs and new impacts expected as a result of increased visitation are outlined, as are options and avenues for site conservation and management.

research topics and data needs for the future. Because the significance and scientific value of Anasazi and Fremont structural sites are more obvious and also discussed by others in this volume, I limit my discussion to the more ephemeral, but no less important, sites occupied by hunter-gatherers before and after the Anasazi and Fremont. Properly managing the Monument's archaeological sites and ensuring their ongoing integrity are essential to future research efforts and fulfilling President Clinton's mandate to preserve and protect them for generations to come. To help achieve these goals, I also offer some factors to consider during the planning process and suggest some management strategies that will help protect the sites.

Research Prospects

Two recent overviews concerning archaeology in the Grand Staircase-Escalante National



Monument (Madsen, 1997; Metcalfe, 1998) indicate that relatively little is known about the Archaic period. While this lack of current knowledge could be interpreted to result from sparse occupation, this is not the case. Many of the small rock shelters and ephemeral, open lithic scatters that are so common in the Monument date to the Archaic period. The sparse nature of the Archaic database results from a relative lack of previous research on Archaic sites and site types rather than a lack of occupation.

In the summer of 1983, I directed a sample inventory of 50,300 acres in the Circle Cliffs Valley, now part of the eastern Monument (Figure 1). Previous regional research projects, particularly the Glen Canyon Project, had found few traces of Archaic occupation other than at a few large cave sites (Jennings, 1966,

1980; Jennings et al., 1980; Lindsay et al., 1968). But, based on my then-recent work at nearby Glen Canyon National Recreation Area (Glen Canyon) (Tipps, 1984, 1987) and that of others on large cultural resource management inventories in southern Utah (e.g., Black et al., 1982; Christensen et al., 1983; Hauck, 1979; Kearns, 1982; Schroedl, 1976a), I suspected that the Circle Cliffs inventory area would have a significant number of open Archaic sites.

This is exactly what I found. All but one of the prehistoric sites with diagnostic surface artifacts dated to the Archaic period (Tipps, 1988); these sites were all open lithic scatters or small rock shelters. On the basis of the inventory, I concluded that Archaic-period hunter-gatherers used the Circle Cliffs Valley during the course of their seasonal round in a

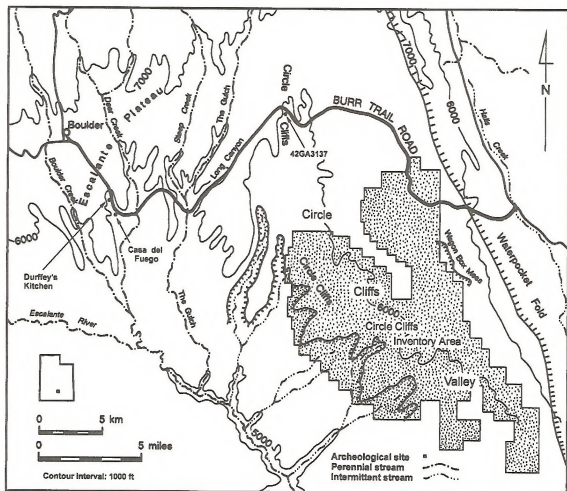


Figure 1. Topographic map showing the locations of the Circle Cliffs cultural resources inventory area and selected archaeological sites along the Burr Trail road in the eastern part of the Grand Staircase-Escalante National Monument.



manner similar to that described ethnographically by Kelly (1964) for the Southern Paiute. Some of the Archaic sites appeared to have substantial deposits and architecture, leading me to suspect that the area was used on more than just an ephemeral basis (Tipps, 1988). Even so, it is unlikely that all aspects of the annual settlement pattern are represented in the inventory area. The area does not have the types and abundance of food resources necessary to sustain year-round occupation. In addition, modern hunter-gatherers occupy areas much larger than the Circle Cliffs Valley during the course of their annual round (e.g., Kelly, 1995; Thomas, 1983). Also, the inventory area composes only a small part of the territory utilized by the ethnographic-period Kaiparowits band of the Southern Paiute (Kelly, 1964), who also practiced a hunting and gathering lifeway.

Instead of being confined to the Circle Cliffs Valley, local Archaic populations used a much larger annual territory, one that probably included the three major elevational-environmental zones of the region: the lowlands and canyons along the Colorado River, the drier uplands or midlands, and the highlands (Geib, 1996; Tipps, 1984, 1987). The Circle Cliffs Valley appears to have been inhabited during the warmer months to procure and process seeds (see Coulam, 1992a, 1992b), small game, and possibly roots. Because of its midlevel elevation with abundant fuel wood and relatively easy access to both the highlands and lowlands, the Circle Cliffs inventory area may have also been used for semipermanent base camps during multiple seasons (see Kelly, 1964). This possibility is supported by the presence of several pithouses and mid-dens, although the scarcity of year-round water sources may have been a limiting factor.

Further research is needed to test these interpretations and place the Archaic occupation of the Circle Cliffs Valley within a larger regional context. The settlement/subsistence model described by Kelly (1964) for the ethnographic-period Southern Paiute provides an excellent departure point from which to initiate such research, but its applicability to the local

Archaic situation must be tested instead of assumed *a priori*. The large size of the Monument and its diverse array of environmental settings make it an ideal location for such studies. Ultimately, however, a complete understanding of the local Archaic settlement/subsistence systems can only come in the context of an even larger regional setting, one that includes areas both inside and outside the new Monument.

Initially, the complete lack of Formative-period sites in the Circle Cliffs inventory area came as a surprise because both the Anasazi and Fremont were known to have used the general area (Hauck, 1979; Lister, 1959; Suhm, 1959) and Formative-period sites such as the Coombs site (Lister and Lister, 1961) and Lampstand Ruins were known in the immediate area. The picture became clear when I analyzed the local environmental data. The Circle Cliffs inventory parcel was defined to mirror the distribution of formations with tar sands potential. Even though it was in the pinyon-juniper woodland, the project encompassed the most rugged, dry, and inhospitable country in the area—basically, the Moenkopi, Shinarump, and Chinle Formations. It obviously offered ample resources for hunting and gathering, at least on a part-time basis, but was unsuitable for farming.

I proposed that Formative-period farmers maintained their habitation sites in surrounding areas that offered more favorable environmental conditions, and that they used more environmentally marginal areas like the Circle Cliffs inventory area only on a temporary basis to procure toolstone and certain wild resources (Tipps, 1988). At the time, I assumed that the availability of farmable land was a key factor in Formative-period site location, but McFadden (1997) has recently suggested that proximity to winter deer range was seasonally important. In any case, the inventory clearly showed that Archaic- and Formative-period peoples had different settlement patterns that were directly related to the distribution of resources critical to their economic situation. Fleshing out the details of these differing settlement patterns continues to be an



important research topic in the Monument and one of several currently being investigated along the Waterpocket Fold (Janetski and Kreutzer, 1997; Janetski and Talbot, 1998).

In addition to showing that the area had a substantial Archaic occupation, and that Archaic- and Formative-period groups had different settlement strategies, the Circle Cliffs inventory offers another lesson worth emphasizing here. Sites in my marginal project area were highly clustered in the most environmentally favorable and resource-rich areas. In other words, site density and location were highly correlated with environmental conditions. This and the differences I observed between Archaic- and Formative-period settlement patterns suggest that this correlation applies on a larger scale outside the Circle Cliffs project area. Indeed, McFadden (1996) reports 37 sites/mi² in an area of the southern Monument. I found approximately 7 sites/mi² in the Circle Cliffs inventory area, which is relatively consistent with the finds of other researchers who have also worked in the less environmentally favorable areas (e.g., Christensen et al., 1983; Halbert and Gualtieri, 1981; Hauck, 1979; Kearns, 1982; Keller, 1987); average site densities encountered by these researchers range from approximately 5 to 11 sites/mi². This variation suggests that it will be difficult to accurately predict not only site density in poorly known areas of the Monument, but also total site count in the Monument without considerably more data than now exist. The Monument has a great diversity of habitats and huge variation in elevation, environmental conditions, and available resources. Large-scale inventories covering a full array of the Monument's environmental settings are needed to better understand how this variability played into prehistoric settlement/subsistence systems.

The Circle Cliffs inventory provided some additional food for thought that crystallized a few years later with the publication of an article by Berry and Berry (1986). In 1976, Schroedl (1976b) suggested population levels were low during the Middle Archaic, and in 1986, Berry and Berry (1986) argued for a

1000-year regional abandonment during this same period.

If these assertions were correct, as potentially indicated by the near absence of Middle Archaic occupations at major northern Colorado Plateau Archaic cave sites, I wondered why half of the datable sites in the Circle Cliffs inventory area were Middle Archaic and why Middle Archaic sites had been recorded on so many other large inventory projects in central and southern Utah (e.g., Brown, 1985; Christensen et al., 1983; Hauck, 1979; Kearns, 1982; Montgomery et al., 1982). A possible answer was obvious. Most of what was known about the Archaic at that time came from major cave sites (e.g., Sudden Shelter, Cowboy Cave, Dust Devil Cave), but the Middle Archaic sites in the Circle Cliffs inventory area and those found on other regional inventories were mostly open sites. This fact suggested that the near absence of Middle Archaic occupation in major cave sites (and hence the conclusions regarding low population levels and a hiatus) resulted not from a regional abandonment, but from a major, unrecognized change in settlement patterns that led to less use of cave sites and greater use of open sites. Because few open sites had been investigated, this change in settlement patterns might help explain why the Middle Archaic appeared to be so poorly represented.

Due to the warmer and drier conditions that were thought to have prevailed during Middle Archaic times on the northern Colorado Plateau, most archaeologists attributed the purported hiatus or declining population levels to deteriorating environmental conditions. Some believed that Middle Archaic people emigrated to regions with more favorable environmental conditions (e.g., Benedict, 1979; Berry and Berry, 1986). Others suggested that at least some people focused on more desirable locales or refugia within the region, such as at higher altitudes and along perennial watercourses (e.g., Copeland and Webster, 1983; Reed and Nickens, 1980). Given that Middle Archaic sites had been found on inventory projects in southern Utah, the latter scenario seemed the more plausible of the two, but not



entirely accurate given that many of the known Middle Archaic open sites were at midlevel elevations and away from perennial water sources. The Circle Cliffs project area, for example, lacked the characteristics archaeologists normally associate with a refugia during warm and dry times, but contained several Middle Archaic sites. This led me to wonder whether their proximity to higher elevations made them attractive.

The opportunity to test some of these ideas and questions came a few years later when P-III Associates undertook testing and excavation of 12 prehistoric sites along the section of the Burr Trail road between Boulder and the western boundary of Capitol Reef National Park. This section of road is just north of the Circle Cliffs inventory area discussed above (see Figure 1). The Burr Trail project area traversed portions of the Escalante Plateau, Circle Cliffs, and Circle Cliffs Valley. As such, it contained a wider variety of environmental settings and available resources than the Circle Cliffs inventory area. It also bisected several perennial watercourses.

Three of the 11 open sites investigated during the project date to the Middle Archaic (Tipps, 1992). Our understanding of these sites is incomplete because each had been truncated by the Burr Trail road prior to our investigations. In addition, our excavations were understandably limited to the road right-of-way (ROW). Even so, the results were sufficient to determine that all three sites were residential bases, probably used for extended camping. All three sites also had plant-processing areas typified by groundstone associated with either unlined hearths, roasting pits, and storage pits, or a large area of decayed organic debris.

One site, Durffey's Kitchen near Boulder, Utah, on the Escalante Plateau, was situated in a dune near a well-watered drainage. The ROW had a midden, scattered flakes, a moderate-size groundstone assemblage, and a cluster of nine unlined pits. Most of the pits were used as hearths or roasting pits; one was a storage feature. Some may have also been used to conduct lithic heat treatment. The prehistoric

ground surface in most parts of the ROW had been truncated by road work prior to our investigations, so there was no opportunity to investigate activity areas, living surfaces, or the surface of origin for any of the features. However, the presence of trash from a wide range of processing, manufacturing, maintenance, and domestic activities, as well as the evidence of storage suggest extended camping. This site has a 2-sigma, tree-ring corrected age range of 4040-3390 B.C., dating it to the Middle Archaic hiatus proposed by Berry and Berry (1986).

A spatially distinct Middle Archaic component was also identified at the nearby Casa del Fuego. The Middle Archaic component was characterized by an indurated use surface deeply buried within a dune. Associated with this surface were a small assemblage of chipped stone and groundstone artifacts and six unlined pits that appear to have been hearths, roasting pits, and/or storage pits. These cultural manifestations are believed to represent a plant-processing area potentially associated with more extensive occupational deposits outside of the ROW. This component has a 2-sigma, tree-ring corrected age range of 4940-4530 B.C.

The third Middle Archaic site, 42GA3137, was located on a bench near an ephemeral drainage in the western Circle Cliffs Valley. It had an artifact scatter and large surface stain that was at least 5 by 9 m across. The feature yielded insufficient charcoal for dating, but the presence of Rocker Side-notched points dates the site to the Middle Archaic. The excavations showed that the stain was caused by decayed organic debris that accumulated on top of the prehistoric ground surface. Due to its nature and association with groundstone, I believe it is the remains of plant refuse discarded around a plant-processing area.

The work at these three sites supports two important conclusions. First, there was no wholesale abandonment of the area during the Middle Archaic. The idea of abandonment was based on the near absence of Middle Archaic occupations in major excavated cave sites, but



Middle Archaic people had a different settlement strategy than other Archaic people, one that emphasized different site type(s). Second, the Burr Trail sites provide compelling evidence that open sites formed an important aspect of Middle Archaic settlement patterns. These sites were not limited to ephemeral camps used for just an overnight stay. At least some open sites were used by collectors for extended camping, intensive plant processing, and food storage. These finds suggest that by emphasizing cave site excavations to learn about the Archaic, we have inadvertently overlooked what now appears to be more than just a sparse Middle Archaic occupation.

There are now enough radiocarbon-dated Middle Archaic sites to refute Berry and Berry's (1986) claim regarding a Middle Archaic hiatus (see Geib, 1996). Schroedl (1976b) may still be correct that population levels were at an all-time low during the Middle Archaic, but this will not be adequately demonstrated until more work is done on the types of sites favored during the period. The Burr Trail project showed that these sites include open sites. Work elsewhere shows that small, sheltered sites adjacent to reliable water were also important (Geib, 1996; Tipps, 1995).

Finding and investigating such sites may be more difficult than it sounds. The Middle Archaic component at Casa del Fuego was buried by more than a meter of sterile sand and had no visible surface indications. We found it while investigating a later component. At Duffey's Kitchen, the presence of the Burr Trail road was fortuitous. Without the road, the site would have appeared on the surface as another typical, undated lithic scatter with little apparent potential for addressing important research questions. It was only because the road grader exposed the midden that the site was recognized as having research potential. And, it was only because the road grader later truncated the tops of the pits, exposing them on the surface, that we found and were able to investigate the cluster of pits south of the main site area.

Research of the past decade suggests that local conditions were indeed warmer and drier during the Middle Archaic (see Geib, 1996), but it is clear that the adaptive response was not one of wholesale regional abandonment. However, the alternative explanation—that people moved to more favorable environmental settings such as high-altitude areas, lake margins, and perennial water sources—does not appear to be the complete story. Certainly, many of the known Middle Archaic sites fulfill these predictions, for example, the Middle Archaic rock shelters along the Colorado River in Glen Canyon (Geib, 1996), the open and sheltered sites near perennial water sources in the Needles District Canyonlands National Park (Canyonlands) (Tipps, 1995), and open sites in the high elevations of the central Wasatch Plateau Uplands in central Utah (McDonald, 1993). But the Burr Trail sites, and many other Middle Archaic open sites that have been found on various inventories in southern Utah, do not fulfill the model's predictions.

Casa del Fuego and Duffey's Kitchen are near watercourses, but these watercourses are not perennial now nor would they have been during Middle Archaic times. There is no reliable water near site 42GA3137. These three Burr Trail sites lie at about 6,000 feet, a midlevel elevation. We can probably all agree that middle Archaic people had to adapt to changing environmental conditions, but we apparently need to broaden our views on how they adapted to warmer and drier conditions and what constituted an environmentally favorable area. It may be that the proximity of the Burr Trail area to higher elevation areas such as Boulder Mountain and the Aquarius Plateau made it attractive for occupation. Sites positioned near these high-elevation land masses would have provided excellent opportunities for serial foraging and collecting (see Binford, 1980; Hogan et al., 1991). By this I mean that prehistoric people could have coordinated resource procurement to match the phased availability of resources maturing at progressively higher elevations throughout the season. In any case, it is clear that Middle Archaic settlement patterns and adaptive



strategies were more complex than current models take into account, and much more work is needed to better understand this time period. The eastern part of the Monument may be an ideal location to further investigate this issue because Middle Archaic sites occur in this area.

Another important research issue concerns the transition from hunting and gathering to an agriculturally dependent lifeway. In the lower Escalante drainages, a few miles south of the Burr Trail, Geib (1996) has good evidence of substantial agriculture in the centuries just after Christ. Two Burr Trail sites—Horse Canyon Rockshelter and Casa del Fuego—were also occupied at this time (Tipps, 1992), but neither has any evidence of agriculture. Instead they reflect a totally Archaic subsistence pattern with an emphasis on processing wild seeds (Coulam, 1992a, 1992b; Schroedl and Tipps, 1992).

The absence of domesticates at the two Burr Trail sites does not appear to be the result of short-term or ephemeral site use. The relevant component at Casa del Fuego has a pithouse dating to the late A.D. 400's or early A.D. 500's; it appears to have been inhabited over an extended period of time (Tipps, 1992). Nor does the absence of domesticates appear to be the result of sampling error at the two sites—both were sampled extensively for flotation. Horse Canyon Rockshelter was intermittently occupied from approximately 1100 B.C. to A.D. 1300 or later, and had 21 features within our excavation block. None of the 10 unlined and slab-lined hearths that definitely or potentially date to the centuries around and after A.D. 1 contain domesticates (Coulam, 1992a; Schroedl and Tipps, 1992). Another possible explanation, a lack of arable land, also seems untenable. McFadden (1997) notes the presence of farmable land near Boulder and in portions of the Circle Cliffs, the general locations of Casa del Fuego and Horse Canyon Rockshelter, respectively. In addition, arable land was noted near both sites by the project crew.

Because both the Burr Trail (Coulam, 1992a, 1992b; Tipps, 1992) and lower Escalante

drainage (Geib, 1996) data seem well-substantiated, the obvious question is, among contemporaneous sites, why do some have evidence of agriculture while others do not? The answer may relate to the presence or absence of environmental conditions necessary for raising the earliest domesticates. Matson (1991) believes that the first successful maize horticulture on the Colorado Plateau would have been in low-elevation areas where floodwater farming was possible. This ideal habitat occurs in the Glen Canyon lowlands, including the Escalante drainages (Geib, 1996), but not in the vicinity of the Burr Trail sites. Thus, it may be that the lower Escalante drainage sites represent some of the earliest local attempts at farming, which later spread to surrounding areas where only dryfarming was possible. Alternatively, the presence of domesticates at some, but not other, sites of similar age may reflect seasonal factors, annual variability in subsistence strategies such as that discussed by Simms (1986a) for the Fremont, or a combination of these and other explanations.

Another important issue concerns the mechanism(s) responsible for introducing agriculture into this area, that is, whether it was adopted by resident populations, introduced through an influx of people already practicing a fully agricultural lifeway, or a combination of these. Given what we know today, which is limited, a possible scenario may be one similar to that posed by Talbot and Richens (1996) for Steinaker Gap. They suggest that:

Basketmaker II nuclear or extended family groups, experienced in maize agriculture, would have spread northward from the more populous regions of northern Arizona, seeking the best arable land...Such groups would have been minority populations in a sea of hunter-gatherers. Enculturation in these settings was likely reciprocal, with the immigrant farmers sharing knowledge of agriculture and associated technologies... But with the people themselves inevitably being swallowed up in the local, larger gene pool.



If a similar scenario is applied to the lower Escalante drainages and Burr Trail area, small groups of experienced farmers may have initially introduced agriculture into the favorable environmental locale of the lower Escalante drainages. From there, agriculture may have gradually diffused among the indigenous hunter-gatherer populations living in the surrounding area. The latter part of this explanation meshes with Janetski's (1993) conclusion that the area "north of the traditional Anasazi region" was typified by a gradual transition from a hunting and gathering to agricultural lifeway from the first introduction of agriculture until approximately A.D. 500. This is only one possible and admittedly simplistic explanation for the local introduction of agriculture, but the purposes of this example are to highlight that there are many important research issues surrounding the adoption of agriculture and to point out that the Monument is an ideal location to study them.

Before closing this section, I want to briefly point out two other research topics that deserve attention. I recently proposed dates of approximately 1900 B.C. to A.D. 300 for Barrier Canyon style rock art (Tipps, 1995). Although Barrier Canyon rock art is not exceedingly common in the Monument, it does occur (Cole, 1990), and there may be opportunities to test and refine the proposed dates. Such research could have important bearing on our understanding of cultural and ethnic boundaries, as well as interactions between fully agricultural versus hunting and gathering groups during the transition period to an agricultural lifeway (see Geib, 1996; Tipps, 1995).

Another set of important research topics pertains to the poorly known Late Prehistoric period. Known sites are relatively rare (Madsen, 1997), but like the Archaic, this may be the result of a weak database rather than sparse occupation. Ethnographic data indicate that the Southern Paiute inhabited much of the Monument, and several Late Prehistoric sites were documented or tested during the Circle Cliffs inventory (Tipps, 1988) and Burr Trail excavation (Tipps, 1992) projects,

respectively. Like the Archaic sites, these sites tend to consist of small lithic scatters, sometimes with surface features such as hearths, or thin strata in small rock shelters attesting to ephemeral use. Initial work on the Late Prehistoric should focus on locating, identifying, and documenting such sites. Kelly's (1964) description of local Southern Paiute settlement patterns should prove invaluable for developing models to aid in this process.

Management Recommendations

This section of the paper discusses some management issues and options. The first set of suggestions pertains to investigating archaeological sites. The second set pertains to protecting them.

Investigating Archaeological Sites

An important step in preparing a management plan for archaeological sites in the Monument is developing a comprehensive and authoritative overview of what work has been done and the status of current science. Such a compilation will help identify gaps in our knowledge and make it easier to define relevant research issues and topics. An overview is already being developed as a cooperative effort between the Utah Museum of Natural History and Bureau of Land Management.

One suggestion I have is that the overview include an assessment of the adequacy of earlier inventory work. Methods and values change through time and as new data become available. Sometimes this renders earlier work inadequate or incomplete. For example, during three seasons of inventory work in nearby Glen Canyon, I observed that only approximately 50 percent of the actual sites in areas inventoried during the late 1950's and early 1960's were discovered and recorded. During a later project I did in Canyonlands, as few as 30 percent of the actual sites in some areas



that were inventoried during the mid 1960's were discovered and documented. The thoroughness of these early inventories was acceptable when they were done, especially considering project constraints, but would not be adequate today.

The overlooked sites in Glen Canyon and Canyonlands tended to be the smaller and less spectacular properties such as lithic scatters, petroglyphs, and open sites with limited architecture, but also included small- to medium-size cliff dwellings and habitations. These oversights resulted in some substantial interpretive errors that stood in the literature well into the 1980's and 1990's. A classic example concerns the Archaic period. Due to the emphasis on more visible and striking sites and the lack of an Archaic point typology, Jennings (1966) in Glen Canyon and Sharrock (1966) in Canyonlands concluded there was no significant occupation prior to Basketmaker II and Pueblo II, respectively. We now know that both areas have a long and rich history of human occupation.

Besides developing an overview, a large-scale, regional inventory of the Monument needs to be initiated to better define the number, nature, and distribution of extant archaeological sites, as well as important environmental parameters. As my earlier discussion illustrates, inventory is also essential to generating new hypotheses that can be tested by ongoing research. Assuming that complete inventory of the Monument will not be possible for years to come, if ever, a statistical sampling strategy may be the best way to select areas for inventory. Such a sample would provide data to estimate population parameters, which should be useful for developing a viable management plan for archaeological sites. Generating accurate, precise, and reliable estimates of population parameters depends on having an unbiased and statistically representative data set. Probability sampling, particularly a simple random sample, is the most effective way of obtaining such a data set (Asch, 1975). Consideration might be given to using 160-acre quadrats to make the data compatible with several large inventories that have already

been conducted in the Monument (e.g., Christensen et al., 1983; Hauck, 1979; Kearns, 1982; Tipps, 1988). Supplemental sampling in areas that receive or are expected to receive high visitation is probably also appropriate. The information provided by such inventories might be useful in devising ways to better protect archaeological sites in high-use areas.

Simple hearth testing projects done in the context of inventory are an inexpensive way of generating more information about sites than can be obtained from surface inventory alone. During recent, multiyear projects in Glen Canyon (Geib, 1996) and Canyonlands (Tipps, 1995), such testing provided chronological and subsistence data that were relevant to addressing methodological issues and regional research problems. In Canyonlands, for example, the testing showed that: many small, discrete, lithic scatters are multicomponent; a newly identified projectile point type dates to the Early Archaic; and an area lacking surface evidence of occupation during the Terminal Archaic and Early Formative was actually inhabited during those time periods. The work in both areas helped generate information necessary to refute the large-scale abandonment of the Colorado Plateau proposed by Berry and Berry (1986) between approximately 1250 B.C. and A.D. 50. A similar testing program in the new Monument would likely be equally rewarding. The recent Glen Canyon and Canyonlands projects also showed that multidisciplinary paleoenvironmental investigations, even on a relatively small scale, can significantly add to the research results of regional inventories (see Geib, 1996, and Tipps, 1995, for example).

Another inexpensive activity that proved to be fruitful for research purposes on the Canyonlands project was collecting samples of raw material from lithic sources encountered during inventory and initiating a lithic type collection for the Park. The availability of these comparative samples made it possible to identify specific raw materials in site assemblages during inventory, which subsequently allowed us to generate hypotheses and interpretations that can be tested during future projects. More



importantly, perhaps, the samples will be available for comparative purposes on future excavation projects when the cost of searching for and collecting such samples would be prohibitive. When lithic raw materials in a collection can be correctly identified and attributed to particular sources or ranges of sources, insights can be gained into settlement/subsistence systems, range size, mobility, and possible trade relationships between groups (Andrefsky, 1994; Bamforth, 1986; Kelly, 1988; Parry and Kelly, 1987).

I also suggest that excavations be undertaken to better understand the archaeology of the Monument and generate new interpretive information for visitors. These investigations should be carefully thought out and accompanied by appropriate research designs written in advance of any field work. If funding for excavation is limited, sites planned for development and interpretation should be emphasized because development and visitation will likely damage their scientific research potential. Finally, I want to emphasize that during all types of archaeological investigations, consideration should be given to all site types. Even sites that appear ephemeral on the surface may hold important information. It is not always possible to judge the potential of a site from its surface indications.

Protecting Archaeological Sites

As noted in the introduction, one of the reasons President Clinton established the Monument was to preserve and protect archaeological sites. Ironically, however, creation of the Monument is a two-edged sword. Sites will be protected from most development projects, but will face new threats as a result of heightened public awareness of the area and a huge concomitant rise in visitation. Increased visitation significantly accelerates impacts to archaeological sites (e.g., Schroedl, 1976c), which are fragile resources that cannot be replaced.

During a total of nine seasons of field work in Glen Canyon and Canyonlands, I had the opportunity to personally observe the amount

and types of damage archaeological sites sustained as a direct result of increasing Park popularity and visitation. This damage took many forms. Some damage was deliberate, such as defacing rock art or pushing over walls. Other damage was thoughtless, such as digging in site deposits, collecting artifacts as souvenirs, removing intact roofing material for use as firewood, or urinating and defecating in sites. Still other damage was unintentional, such as driving across or camping on sites, climbing on walls, walking across sensitive deposits, or undermining a structure by walking across the talus slope below it. Some damage was completely unexplainable, for example, building "new" structures. In more than one instance, I saw visitors dismantle, rebuild, and dismantle small, dry-laid structures during the course of a single field season.

Regardless of intent, the damage from increasing visitation was often substantial, always cumulative, and frequently affected the integrity of the site and its future research potential. Most of the highly visible sites in both Glen Canyon and Canyonlands had been completely stripped of surface artifacts. Even open lithic scatters had been surface collected. Previous research has shown that visitors collect artifacts from lithic scatters once the surface artifacts are gone from the more spectacular sites (Francis, 1978). Surface collection, even minimal amounts, can greatly reduce what we are able to learn about a site during surface inventory (Fawcett, 1993:46). Many of the conclusions and hypotheses I developed on the basis of the Circle Cliffs inventory would not have been possible if the area had been as heavily collected as highly visited areas of Glen Canyon and Canyonlands.

Figures 2-4 illustrate some examples of the damage caused by uncontrolled visitation. Figure 2A, taken in 1978, shows a view from the inside of a structure on an ancestral Pueblo site in Glen Canyon. The structure had survived, intact, for approximately 800 years. Figure 2B shows the same structure in 1997. The front wall, missing in the 1997 photograph, is believed to have been inadvertently destroyed by a Park visitor (Christine Goetze,



Figure 2. Paired views taken from the inside of a structure on an ancestral Pueblo site in Glen Canyon National Recreation Area. In 1978, most of the front wall was intact and the foundation was solid (View A, left). By 1997, the front wall had been completely destroyed (View B, right).

personal communication, 1997). This site has less visitation than many other sites because accessing it requires climbing a steep, sandy talus slope and ascending a stone crack or chimney, but the damage during a 19-year period of high visitation was more substantial than that of the previous 800 years.

Another nearby site fared even worse because there is motorized access right to it. Figure 3A shows the intact roof on a kiva in 1978. Like the previous example, this structure had survived mostly intact for approximately 800 years. By 1997, most of the roof had been destroyed (Figure 3B) by people walking on it, using pieces of it for firewood, and taking home pieces as souvenirs. This same site had an intact granary in 1978 (Figure 4A). By 1997, the structure was almost completely destroyed (Figure 4B). Unfortunately, these examples are not isolated incidents. I also want to stress that although all of these examples

are from Glen Canyon, it is not just the presence of Lake Powell that resulted in the nature and extent of the damage. These same types of damage are occurring in areas of Canyonlands National Park that are only accessible on foot. The only difference is that they are occurring at a slower rate. Left unchecked, the damage in Canyonlands will eventually equal the examples shown above in Glen Canyon. The key factors are not the lake, nor visitors who favor motorized recreation, but access (whether by boat, vehicle, or foot), lack of protective measures and adequate controls on visitors, and the lack of a sufficiently strong public education program.

I have several suggestions on what can be done to lessen the impacts of visitation. A strong program of public education is essential. Visitors need to be informed of what activities and actions are acceptable at archaeological sites and what are not. They are more likely to



Figure 3. Paired views of a kiva on an ancestral Pueblo site in Glen Canyon National Recreation Area. In 1978, large portions of the roof were preserved (View A, left). In 1997, only a small section of the roof remained (View B, right).

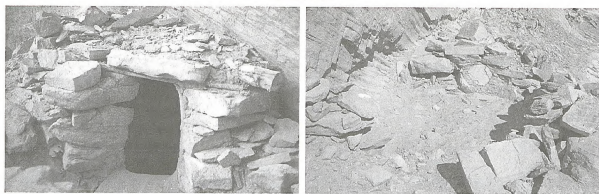


Figure 4. Paired views of a granary on an ancestral Pueblo site in Glen Canyon National Recreation Area. In 1978, the granary was completely intact except for the hatch cover and the end of a roof beam that was removed by archaeologists for dendrochronological dating (View A, left). In 1997, only the foundation of the structure remained (View B, right).

respect and adhere to restrictions if they understand why the restrictions are needed, and do not feel as though a government agency is arbitrarily dictating what they can and cannot do. Many visitors I have encountered on archaeological sites are surprised and upset when they learn that their actions are damaging the sites they so love and enjoy. Often, they are not aware that collecting five potsherds or walking on a wall to get a better picture is damaging a nonrenewable resource. Education is not likely to stop a pothunter or determined vandal, but will probably deter most casual visitors, who cumulatively, appear to be doing the majority of the damage. Public education programs are most effective when education takes place before the visitor encounters an archaeological site. As such, it may be useful to begin the education process at toll booths or contact stations as visitors first enter the Monument.

Public education can and should take many forms to appeal to the widest possible range of visitors. Possibilities include building museum and roadside exhibits, sponsoring hands-on activities, offering ranger lectures and tours, and widely distributing both free and minimally priced printed materials. Appropriate sites should also be developed and interpreted for visitor enjoyment and promoted so that visitors are aware of their presence. These sites need to be excavated before they are developed to recover all important scientific information. Such excavations will also provide opportunities for public participation in archaeological projects.

The Monument is large and has a diverse array of archaeological sites. The number and diversity of developed sites should be correspondingly large and diverse, because visitors who have enough opportunities to visit interesting archaeological sites (that are developed and can sustain high levels of visitation) are less likely to visit more remote, undeveloped sites that are not able to withstand high levels of use without incurring significant damage. However, for this to occur, visitors must be satisfied with their visits to developed sites. Among other things, satisfaction depends on the developed sites being made easier, more enjoyable, and more rewarding to visit than undeveloped sites (Gale and Jacobs, 1987). Providing toilet facilities, places to rest along the path to the site, and good vantage points for photographs were identified as important factors in one study (Gale and Jacobs, 1987). Among many visitors I encountered in Glen Canyon, a lack of obvious development leading to a sense of visiting a pristine site was crucial. Gale and Jacobs (1987) note that visitor needs vary from place to place and suggest that visitors be interviewed to find out what level of development and interpretation will satisfy their needs. Different levels of development at different sites may be appropriate. Gale and Jacobs (1987) also offer numerous suggestions regarding how to protect developed sites.

Given President Clinton's mandate to preserve and protect the Monument's archaeological sites for public enjoyment, and that most



archaeological work is ultimately funded by the public, the Bureau of Land Management has an important obligation to share the Monument's archaeological sites with the public. Even if it were possible, it is not appropriate to close off the Monument's archaeological sites in the name of preservation and protection. But, there must be a balance regarding what is shared and what is preserved for the future. Otherwise, as experience has shown in other southern Utah Parks, the entire archaeological resource base will degrade and deteriorate, thus defeating two of the President's purposes of establishing the Monument—preserving sites for public appreciation and future research.

Numerous local and international studies have shown that ease of access is a key factor in whether and how much a site will be damaged (Ahlstrom et al., 1992; Francis, 1978; Gale and Jacobs, 1987; Harden, 1979; Kvamme, 1990; Lightfoot, 1978; Lightfoot and Francis, 1978; Nickens et al., 1981; Schroedl, 1976c; Scott, 1977; Simms, 1986b; Wylie and Nagel, 1989). Simply put, the easier the site is to reach, the more frequent and significant the damage. Lightfoot (1978) states:

It should be recognized that the effects of building roads will go much beyond those sites modified through road construction and maintenance. The construction of roads will increase the flow of people into an area, making the sites located in the immediate vicinity more accessible to pothunters.

Establishing campgrounds, picnic areas, and other recreational sites can have the same effect (Francis, 1978). Because access is a key factor in the nature, extent, and types of damage done to archaeological sites, eliminating or restricting the construction of new roads and other facilities inside the Monument is an obvious solution. But this issue must also be considered on a more specific, site-by-site basis.

Glen Canyon and Canyonlands are models of what the future could hold for archaeological sites in the Monument unless there is early

intervention and proactive planning before significant damage occurs. No one could have foreseen the nature and extent of damage to sites in Glen Canyon and Canyonlands 20 years ago, but the potential for damage to sites in the Monument is foreseeable now. Conscious decisions should be made early on regarding which sites to use for public interpretation and which sites to protect for the future. Those selected for interpretation need to be interpreted and made accessible. Those selected for preservation need to be made less accessible. One of the best means of making sites less accessible is by designating large areas as wilderness. Reducing access not only reduces visitation, it also makes visitors more appreciative of sites they do reach, and thus, less likely to damage them (Gale and Jacobs, 1987). Wilderness is also a very cost-effective means of reducing visitation, and hence, impacts to archaeological sites, which is important because there will never be enough resources to protect all of the archaeological sites in the Monument.

The Utah Professional Archaeological Council (UPAC) is already on record as supporting wilderness as a means of protecting large numbers of archaeological sites. In letters to the Governor and the Utah Congressional delegation on behalf of UPAC, Davis (1995a, 1995b) states:

Clearly, maintaining roadless areas is the largest and least costly deterrent to pothunting, inadvertent vehicle damage, and vandalism. For this reason we believe that designating the maximum amount of wilderness possible will provide the maximum protection for the maximum number of archaeological, historical, and sacred Native American sites (Davis, 1995a).

Furthermore, it is essential that wilderness areas be large and numerous. Otherwise, there is a significant risk of visitor use being concentrated on a few archaeological sites, thus hastening their deterioration. Large areas are also necessary to ensure the preservation of entire prehistoric settlement and subsistence systems which



typically span a variety of habitats in the larger mountain-desert ecosystem (Davis, 1995b).

One of our ultimate goals as archaeologists, anthropologists, and historians is to preserve and protect cultural properties....we believe that wilderness designation could be one of the most effective mechanisms of preserving and protecting the rapidly diminishing traces of Utah's heritage (Davis, 1995a).

Even if large areas of the Monument are designated as wilderness, undeveloped sites throughout the Monument will still be at risk. Some sites may need to be fenced. Access to the most archaeologically sensitive areas (e.g., the Kaiparowits Plateau) should probably be discouraged, if not controlled, and possibly limited through a permitting system. Limiting group size in the back country can also be an effective means of controlling visitor-induced damage. Regular monitoring of sites for damage is extremely important for early intervention and devising ways of arresting damage as it begins to occur. It is also essential to detecting cases where undeveloped sites are becoming popular visitor destinations by default, without prior planning or the emplacement of mechanisms to protect the site (Gale and Jacobs, 1987). It would be relatively easy and inexpensive to collect detailed baseline data and photographs on site condition during the inventory stage. These data can provide a basis for documenting damage and deterioration in the future. I also suggest frequent ranger patrols and a cyclical stabilization program for all developed and selected other sites. Rigorous enforcement and vigorous pursuit of convictions for illegal offenses should also be considered.

Finally, a sample of artifacts should be routinely collected from all sites during inventory. In Canyonlands, where a noncollection policy was in place for our inventory work (e.g., Tipps, 1995), many important artifacts—including whole pots—and the data they could

have provided were lost to science forever when visitors took them as souvenirs. Illegal artifact collection is a serious problem that needs to be confronted through public education, but because this will be a long and not completely effective process, it also needs to be combated by professionally collecting a sample of artifacts before they are gone. Even if funding levels prevent the artifacts from being thoroughly analyzed at the time of collection, they can be curated for future collections research.

When President Clinton created the Monument, he gave us a challenge to both study and protect the Monument's archaeological values. Conserving sites while at the same time making them available for visitors to enjoy is a formidable task. I hope that the suggestions offered here will aid in the process and make the task a little easier.

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Mammalian Species Diversity of the Grand Staircase-Escalante National Monument

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ABSTRACT

■ In general, the current understanding of the distribution and abundance of mammals in the southern part of the Colorado Plateau is based on survey work that was completed almost 50 years ago (Durrant, 1952). The relatively few studies that have been conducted since then have tended to be of restricted scope, either geographically or in terms of species covered. Since about 1988, personnel from the U.S. Geological Survey, Biological Resources Division (and its predecessor agencies), have been conducting baseline mammal surveys on most National Parks in the southern part of the Colorado Plateau, including Glen Canyon National Recreation Area, Natural Bridges National Monument, Capital Reef National Park, Bryce Canyon National Park, and Zion National Park, as well as in the Henry Mountains Resource Area administered by Bureau of Land Management. These areas essentially surround the new Grand Staircase-Escalante National Monument, and information from them is pertinent to questions of species diversity and conservation of mammals in the Monument. Correspondingly, data on mammals from the Monument area will contribute significantly to a better understanding of mammals on the southern Colorado Plateau. Data from our baseline surveys in nearby Parks are presented within a context of the status and conservation needs of mammals in this area and the need for baseline surveys in the Monument.

Early information on mammals of the southern Colorado Plateau, especially what is now the Grand Staircase-Escalante National Monument (GSENM), Utah, is limited. Presnall (1938) and Presnall and Hall (1936) reported on mammals from Zion and Bryce National Parks and some of the records reported by Long (1940) and Hardy (1941) came from southern Utah. Conversely, the area to the south, especially the Grand Canyon and Colorado River, has been the subject of many studies. Goldman (1937) noted the importance of the river as a barrier to mammals and Kelson (1951) demonstrated significant variation in mammal species as a result of the river's isolating effects. Other pertinent studies include those of Benson (1935), who provided important information from nearby Navajo Mountain, and Jones et al. (1982), who

contributed a distributional checklist of mammals of the Grand Canyon corridor.

The last synthesis of mammals in Utah (Durrant, 1952) was completed just prior to major roadbuilding efforts that resulted from energy exploration in the area; consequently, many areas of southern Utah were inaccessible. Durrant, his colleagues, and students nonetheless conducted field work as widely as possible, again including the Colorado River (e.g., Durrant and Dean, 1959) and its tributaries. In addition, much of this field work predated some presently used techniques, such as mist netting for bats, so some elements of the mammalian fauna were not well-studied. Hayward et al. (1958) provided overviews of



the upper Colorado River basin studies conducted by investigators from Brigham Young University. Stock (1970) clarified our understanding of distribution and taxonomy for several species of mammals in southern Utah, mostly to the west of the Monument. Hall's (1981) continentwide treatment of mammals includes much information on Utah mammals, but specific localities are restricted to those at the edge of a species' range. Considerable pertinent information on mammals of the Arizona strip, adjacent to Utah and north of the Colorado River, is contained in Hoffmeister's (1986) review of Arizona mammals.

More recent papers that are pertinent to mammals of the Grand Staircase-Escalante include Schafer's (1991) examination of the mammals of the Abajo Mountains to the east, Mollhagen and Bogan's (1997) discussion of the bats of the Henry Mountains just to the north, and Atwood et al.'s (1980) summary of the results of studies on vertebrates in and around the Kaiparowits Basin by personnel from Brigham Young University. Although the Brigham Young University studies resulted in the collection of voucher specimens, apparently many of these specimens have since been lost (N.D. Atwood, personal communication).

In response to information needs of several National Parks on the southern Colorado Plateau, and in recognition of the absence of recent baseline data, personnel from the U.S. Geological Survey, Biological Resources Division, and its predecessor agencies initiated surveys for mammals in this area. These surveys, a critical adjunct to land management activities (Bogan et al., 1988; Stohlgren et al., 1994), began in 1988 and continue at a low level to this day. Data from these surveys that bear on general distribution, taxonomy, and status of mammals are pertinent to an understanding of mammals in the Monument, as in most cases the studied Parks essentially surround the Monument. Conversely, as baseline surveys for mammals are conducted in the Monument, those data will be valuable in helping not only to better understand broad questions of mammalian distribution on the southern Colorado Plateau, but also to help

address specific questions on status and conservation of mammals of this unique area.

Our primary goals in this short paper are to give an overview of the importance of the area to mammals, provide a preliminary list of mammals of the new Monument, and discuss species of special interest or concern.

Methods

Surveys have been conducted in the National Parks adjacent to GSENM for 2 to 3 weeks each year since 1988. On the average, we have visited each Park about 5 times for a total of 10-15 person-weeks of effort; not all Parks were visited in any given field season. The Parks on which we have worked include Bryce Canyon National Park (BRCA), Capitol Reef National Park (CARE), Glen Canyon National Recreation Area (GLCA), Natural Bridges National Monument (NABR), and Zion National Park (ZION); in addition, we have conducted studies (e.g., Mollhagen and Bogan, 1997) in the Henry Mountains Resource Area, administered by the Bureau of Land Management, Hanksville. During our visits we attempt to capture mammals in all distinctive vegetation types within the Park, using a variety of traps for rodents and mist nets for bats. Our studies are specimen-based and vouchers are saved and deposited in the Biological Survey collection of the Museum of Southwestern Biology, University of New Mexico, Albuquerque. Where possible, we scrutinize Park files and databases and talk to Park staff to obtain additional information on mammals. Annual reports with updated lists of mammals are provided to each Park where we work. Permits for our work are provided by the Utah Division of Wildlife Resources and the individual Parks.

We used specimens we collected and standard references on mammals from the southern Colorado Plateau (e.g., Durrant, 1952; Hall, 1981; Hoffmeister, 1986) to develop a preliminary list of mammals of the Grand Staircase-Escalante National Monument. References



mentioned in the Introduction also were used as appropriate. Scientific and vernacular names for mammals generally follow Jones et al. (1997) unless otherwise noted.

Results and Discussion

Zoogeographic Importance of the Grand Staircase-Escalante Region

The Grand Staircase-Escalante area of southern Utah has been identified as a unique area for mammalian speciation and diversity. Kelson (1951) identified this area as the Kaiparowits Subcenter of the Canyon Lands Province, Colorado Plateau Faunal Area, and noted that the mammal fauna was similar to that of the aridlands of northwestern Arizona (Arizona Strip) and that several taxa were not found elsewhere in Utah. Mammals of this subcenter also show close affinities with mammals from the San Rafael Subcenter to the north, but are more distantly related to mammals south (or east) of the Colorado River (Kelson, 1951), which has been more of a barrier to the movement of, and gene flow between, mammals. Durrant (1952), in summarizing the zoogeography of Utah mammals, agreed with Kelson (1951) in recognizing the Grand Staircase-Escalante region as a unique subcenter of mammalian differentiation. Durrant (1952) agreed that mammals of the Kaiparowits Subcenter are most closely related to mammals of the San Rafael area, and that the major portion of the Kaiparowits Subcenter is in Arizona, north of the Colorado River.

Simpson (1964), who examined continentwide patterns, found that species diversity of mammals was related to topographic relief and that the high diversity in the Rocky Mountains extended westward through the Colorado Plateau and then southward into Mexico. To the east, north, and west of the Rocky Mountains and Colorado Plateau, species diversity tended to decline. Hagmeier (1966) examined mammalian distributional patterns

and derived zoogeographic provinces based on faunal similarity. His Kaibabian Province includes the Grand Staircase-Escalante area of southern Utah and part of northern Arizona; mammals in this province show the greatest similarity to the mammals to the south in his Sonoran Mammal Province.

Mammals of the Grand Staircase-Escalante National Monument

Durrant (1952) suggests that the GSENM contains about 62 species of mammals. Atwood et al. (1980) tabulated about 62 in the Utah portion of the Kaiparowits Basin and a total of 72 for the basin as a whole. Our work in southern Utah suggests that the mammalian fauna of the GSENM contains 68 to 81 species of mammals (Table 1). The fact that the distributional status of at least 13 species is uncertain reflects the need for baseline mammal surveys in the Monument. Many of the species whose actual status in the Monument is unknown are high-elevation forms (e.g., *Sorex cinereus*, *Lepus americanus*, *Marmota flaviventris*, *Zapus princeps*, and *Mustela erminea*), and their documented presence will require surveys of appropriate areas to ascertain if they occur. A few others are arid lowland forms (*Macrotus californicus* and some *Perognathus* or *Dipodomys*). The presence of some other species (*Ursus americanus*, *Eumops perotis*, and *Antilocapra americana*) will depend on the presence of appropriate habitat features and some luck in conducting surveys.

The two most speciose groups of mammals at GSENM are rodents, composing about 38 percent of the total mammal fauna, and bats, composing about 25 percent. These two groups, which include a variety of mostly nocturnal and secretive forms, are especially poorly known. Other groups in decreasing order of percent composition are carnivores (19 percent), shrews (7 percent), even-toed ungulates (5 percent), and hares and rabbits (4 percent).

The mammals of the GSENM reflect diverse origins. Most of the high-elevation forms (e.g.,



Table 1. Preliminary list of the mammals of the Grand Staircase-Escalante National Monument, Utah. Species that may not occur are noted with a question mark (?); most of these species are high-elevation forms. Species presumed to be extirpated are noted with a plus sign (+); type localities are abbreviated as TL. Specific nearby localities are from Hall (1981) unless otherwise noted. Pertinent captures or observations of mammals from adjacent (BRCA, CARE, GLCA) or nearby (NABR, ZION) National Parks are listed by Park acronym (see methods for names).

INSECTIVORA (Shrews)

- Sorex cinereus* ? (Wildcat Ranger Station, Boulder Mt., UT)
S. merriami [BRCA]
S. maniculatus [BRCA]
S. nanus [BRCA]
S. palustris [Kaiparowits Plateau, UT; CARE, ZION]
S. preblei ?
Natasorex crawfordi [CARE (Haddenbach, 1978), ZION]

CHIROPTERA (Bats)

- Myotis californicus* ? [Virgin Narrows, AZ]
Myotis californicus [BRCA, CARE, GLCA, NABR, ZION]
M. ciliolabrum [BRCA, CARE, GLCA, NABR vic.]
M. evotis [BRCA, NABR, ZION]
M. lucifugus ? [BRCA]
M. thysanodes [BRCA, GLCA, NABR, ZION]
M. volans [CARE, NABR, ZION]
M. yumanensis [CARE, GLCA, NABR, ZION]
Lasionycteris noctivagans [BRCA, CARE, NABR, ZION]
Pipistrellus hesperus [CARE, GLCA, NABR, ZION]
Eptesicus fuscus [BRCA, CARE, GLCA, NABR, ZION]
Lasiorus blassevilli ? (Washington and Carbon counties)
L. cinereus [BRCA, CARE]
Eudermomacrotus [BRCA (vicinity), CARE, NABR, ZION]
Idionycteris phyllotis [CARE, GLCA, NABR]
Carynorhinus townsendii [CARE, GLCA, NABR]
Antraeus pallidus [BRCA, CARE, GLCA, NABR, ZION]
Tadarida brasiliensis [CARE, GLCA, NABR, ZION]
Nyctinomys macratus [NABR]
Eumops perotis ? [Nath Kaibab Plateau, Mike Herder, pers. commun.]

LAGOMORPHA (Hares and Rabbits)

- Sylvilagus nuttalli* [BRCA]
S. odocoileus [CARE, GLCA, NABR, ZION]
Lepus americanus ? [21 mi N Escalante, UT]
L. townsendii ? [Kanab, UT]
L. californicus [BRCA, CARE, GLCA, NABR, ZION]

RODENTIA (Rodents)

- Eutamias minimus* [BRCA, ZION]
E. dorsalis [5 mi NW Kanab, UT; BRCA, CARE, ZION]
E. hoplandi (= *rufus*) [CARE, GLCA, NABR]
E. umbrinus [18 mi N Escalante, UT; BRCA, ZION]
Marmota flaviventris ? [Lang Valley, Morkagunt Plateau, UT; BRCA, CARE, ZION]
Ammospermophilus leucurus escalante [TL: 2 mi S Escalante; Kanab, UT; CARE, GLCA]
Spermophilus lateralis ? [BRCA, ZION]
S. variegatus [BRCA, CARE, GLCA, NABR, ZION]
Tamiasciurus hudsonicus ? [BRCA, ZION]
Glaucomys sabrinus ? [BRCA]

- Thomomys talpoides* ? [Birch Creek, Escalante Mts.; 18 mi N Escalante, UT; BRCA, ZION]
T. battae pliniostris [TL: Zion NP]
Perognathus parvus trumbullensis [TL: Mt. Trumbull, AZ; BRCA, CARE, GLCA]
P. langimembris orizonensis [TL: Jacobs Pools, Houserack Valley, AZ; Kanab; GLCA]
P. f. formosus [TL: St. George, UT; GLCA; includes *domisoxensis*]
Dipodomys ordii cupulidinus [TL: Kanab Wash, AZ; Calif Ck., Escalante R., UT; BRCA, CARE, GLCA]
D. microps leucotis [TL: Houserack Valley, AZ; not known from Utah]
Castor canadensis [CARE, GLCA]
Reithrodontomys megalotis [BRCA, CARE, GLCA, NABR, ZION]
Peromyscus boylii [BRCA, CARE, GLCA, NABR, ZION]
P. crinitus [BRCA, CARE, GLCA, NABR, ZION]
P. maniculatus [BRCA, CARE, GLCA, NABR, ZION]
P. truei [BRCA, CARE, GLCA, NABR, ZION]
Onychomys leucogaster melanophrys [TL: Kanab, UT; CARE, GLCA]
Neotoma cinerea [BRCA, CARE, GLCA, NABR, ZION]
N. lepida [CARE, GLCA, ZION]
Micratus longicaudus [BRCA, CARE, NABR, ZION]
M. mantanus [BRCA, CARE, ZION]
Lemmus curtus [BRCA]
Onychomys leucogaster [CARE-obsv.]
Zapus princeps ? [10 mi N Boulder, UT]
Erethizon dorsatum [CARE-obsv., GLCA-obsv.]

CARNIVORA (Carnivores)

- Canis latrans* [BRCA, CARE, GLCA, NABR]
C. lupus +
Vulpes vulpes [Henrieville, UT; BRCA, CARE]
Urocyon cinereoargenteus [BRCA, CARE]
Ursus americanus ? [CARE]
U. arctos +
Bassariscus astutus [12 mi SW Orderville, UT; BRCA, CARE]
Procyon lotor ? [CARE, ZION]
Mustela erminea ? [Boulder Mt., 8,700 ft, UT; CARE]
M. frenata [BRCA]
Toxidea toxus [BRCA, CARE]
Spilogale gracilis [CARE]
Mephitis mephitis [BRCA, CARE, ZION]
Felis concolor [BRCA, CARE]
Lynx rufus [CARE]

ARTIODACTYLA (Even-Toed Ungulates)

- Cervus elaphus* + [BRCA, CARE; all are introduced Rocky Mt. subsp.]
Odocoileus hemianus [BRCA, CARE, GLCA, NABR, ZION]
Antilocapra americana ? [BRCA, CARE]
Ovis canadensis [CARE, ZION]



Sorex cinereus, *S. palustris*, *Marmota flaviventris*, *Tamiasciurus hudsonicus*, and *Neotoma cinerea*) represent taxa with origins in northern boreal forests or the Rocky Mountains and tend to be restricted to mesic, high-elevation habitats. Other species (e.g., *Sorex nanus*, *S. merriami*, *Sylvilagus nuttallii*, *Perognathus parvus*, and *Lemmus curtatus*) represent, or are related to, Great Basin forms and frequently are most common in shrublands. The bulk of the heteromylid rodents (*Perognathus* and *Dipodomys*) are derived from species in deserts to the south, primarily the Mojave or Sonoran, and typically prefer arid, sandy habitats. A few species (*Lepus townsendii*, *Onychomys leucogaster*, *Antilocapra americana*) have affinities with mammals of the Great Plains, and finally, several bats (*Macrotus californicus*, *Lasiurus blossevillei*, *Tadarida brasiliensis*, *Nyctinomops macrotis*, and *Eumops perotis*) have Neotropical affinities.

There are at least seven subspecies of mammals that are endemic to the Grand Staircase-Escalante—Kaiparowits region. These subspecies, although related to nearby forms, appear to have developed in response to the unique environments of the region. These taxa include a white-tailed antelope squirrel (*Ammospermophilus leucurus escalante*), Great Basin pocket mouse (*Perognathus parvus trumbullensis*), little pocket mouse (*P. longimembris arizonensis*), long-tailed pocket mouse (*P. f. formosus*, including *P. f. domisaxensis*), Ord's kangaroo rat (*Dipodomys ordii cupidineus*), chisel-toothed kangaroo rat (*D. microps leucotis*), and northern grasshopper mouse (*Onychomys leucogaster melanophrys*).

Status and Conservation of Species of Mammals in the GSENM

Several species of mammals that originally occurred in the GSENM have been extirpated from the area; these include *Canis lupus*, *Ursus arctos*, and the native elk, *Cervus elaphus*, which has been reintroduced with animals (presumably of the same subspecies) from the Yellowstone area. The historic status

of the bison, *Bison bison*, in this area is uncertain, but we have chosen to exclude it on the basis of a lack of information.

Some groups of mammals in the GSENM are poorly known and information on their status is desirable. These include most of the shrews, which can be difficult to trap and identify, and most of the bats, which have critical needs for roosts, especially for raising young and hibernating. Many bat species are very sensitive to disturbance and care must be taken in and near roosts; abandoned mines must be surveyed for bats prior to closure for human safety. The actual occurrence of two hares (*Lepus americanus* and *L. townsendii*) is problematic and they may have been replaced by *L. californicus*, a species that seems often to invade disturbed habitats. Nuttall's cottontail (*S. nuttallii*) has been mentioned as a species that may be disappearing from some areas (National Parks; Newmark, 1995), although it is often most active at dawn and dusk and can be difficult to identify. Several of the squirrels are poorly known and information on their occurrence and abundance is desirable. Information on pocket gophers (*Thomomys bottae*) from the Henry Mountains suggests that they may have been affected by changes in land use or by rodenticides (T.R. Mollhagen, personal communication) and information on their status in the GSENM is needed. Flather et al. (1994) provide more information on sensitive species and threats to animal groups in the area, and additional taxa have been listed as species of concern (former Category 2 Candidate Species) by U.S. Fish and Wildlife Service and various State heritage programs.

Of particular importance is the need to obtain information on the seven endemic subspecies of mammals that occur in the area. Not all of these taxa may occur in the GSENM, but this needs to be determined. Once baseline surveys have been conducted and the presence of the taxa ascertained, attempts to obtain population status and trend information should be initiated. We encourage the managers of the GSENM to emphasize those resources of the Monument that are unique to the area, as opposed to placing priorities on taxa that may



be more wide-ranging. Finally, much of the information required for wise stewardship of mammalian natural resources of the GSENM can be obtained from a carefully designed inventory and monitoring program.

Conclusions

It is imperative that baseline surveys of mammals be conducted. Those responsible for the long-term management of the GSENM should be encouraged to discover those taxa of plants and animals that are unique and endemic to the area and to make special attempts to ensure that those taxa remain a functional part of this unique ecosystem.

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Nonnative Brome Grasses in the New National Monument

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ABSTRACT

■ Included within the boundaries of the Grand-Staircase Escalante National Monument are a number of noxious weeds for which the BLM mandates control. In addition to listed weeds are nonnative brome grasses (*Bromus tectorum* and *Bromus rubens*), which can potentially convert native ecosystems to biologically impoverished annual grasslands. Although brome grasses occur virtually throughout the new Monument, they remain at relatively low biomass, with denser stands patchily distributed in former disturbances due to agriculture, road development, and fire. We discuss case studies indicating that this type of distribution often precedes habitat conversion by brome grasses, and we review various investigations related to how and why coverage expands. Measures should be taken to monitor the spread of brome grasses, and management strategies related to road development, tourism, fire, grazing, and habitat alteration and restoration should be consistent with the need to contain the distributions and abundances of these destructive weeds.

One of the greatest potential threats to the ecological integrity of the Grand Staircase-Escalante National Monument (GSENM) is the possible aggravation of invasions of aggressive introduced plants, which are rapidly transforming native plant communities throughout the western U.S. With seeds transported by vehicles, hikers, and livestock, in addition to natural elements like wind, water, and native animal vectors, these plants find an early foothold in roadside ditches, agricultural areas, and recent burns, where native communities have been largely removed. Perhaps due to the low biotic resistance from natives in these areas, and to increased water runoff along improved roads, these exotic species can form dense stands that persist for years. Once established, these species are poised to invade adjacent native communities when conditions are right.

Introduced plant species within the GSENM consist of both "noxious weeds" (Table 1), against which active control measures are being taken, and more pervasive exotics, the control of which is more problematic. Among the most troublesome of plants in the first

category are saltcedars (*Tamarisk ramosissima* and *Tamarisk parviflora*), which invade relatively moist habitats like permanent and temporary watercourses, as well as ditches along improved roads. Conversion of riparian strips from native vegetation to tamarisk can greatly reduce plant and animal biodiversity.

In addition to the noxious weeds listed in Table 1, there are brome grasses (*Bromus*

Table 1. Noxious weeds of the Grand Staircase-Escalante National Monument [courtesy of L. Maxfield].

Common name	Scientific name
Bindweed (wild marning glory)	<i>Convolvulus</i> spp.
Perennial sorghum	<i>Sorghum</i> spp.
Quackgrass	<i>Agropyron repens</i>
Russian knapweed	<i>Acroptilon repens</i>
Scotch thistle	<i>Onopordium acanthium</i>
Whiteloop	<i>Cardaria</i> spp.
Dalmatian toadflax	<i>Linaria dalmatica</i>
Jointed goatgrass	<i>Aegilops cylindrica</i>
Russian olive	<i>Elaeagnus angustifolia</i>
Whorled milkweed	<i>Asclepias subverticillata</i>
Saltcedar	<i>Tamarix ramosissima</i> and <i>Tamarix parviflora</i>



rubens near Lake Powell, and *B. tectorum* at higher elevations), which BLM surveys in the 1980's revealed to be ubiquitous throughout lands now included in the GSENM (P. Chapman, pers. comm.). Although other arid regions of Utah and neighboring western states have been profoundly altered by *Bromus tectorum* (cheatgrass) especially, control of these alien grasses is not mandated, in part because attempts at control are deemed futile.

Moreover, within Monument lands in particular, brome grasses have not yet devastated the landscape through habitat conversion as they have throughout the salt desert shrublands of the Great Basin (Pellant and Hall, 1994; West, 1994). From these shrublands to the edges of the Mojave Desert in the south, the presence of cheatgrass, and its unique seasonal phenology, have contributed to increased fire frequency and the replacement of native shrubs, grasses, and forbs (e.g., Yensen, 1981; Hunter, 1991; West, 1994; Harper et al., 1996). Effects of habitat conversion radiate upward through the food chain, and adverse effects have been documented on pronghorn (*Antilocapra americana*) and deer (Pellant, 1990; Roberts, 1994), small vertebrate prey of eagles and other raptors (Kochert and Pellant, 1986; Nydegger and Smith, 1986), native birds (Dobler, 1994), and insects (Fielding and Brusven, 1994). As summarized by Billings (1994), exotic annual grasses could constitute:

"a genuine threat to the existence of large integrated ecosystems that have existed since the Pleistocene in the relatively arid lands between the Rocky Mountains and Sierra Nevada. These operational ecosystems could disappear over large areas of thousands of square kilometers."

At present, it is not clear what accounts for the relatively innocuous nature of brome within the GSENM. Its ubiquity suggests that the relatively low levels are due not to a dearth of colonists, but to the inappropriateness of the habitat. However, that view could be deceiving, since it is possible that the introduction of new genetic variants (e.g., Pyke and Novak, 1994) could aggravate the cheatgrass problem. Moreover, even if local conditions within the

new Monument are not *presently* conducive to outbreak densities of brome, we cannot count on the problem to remain in check indefinitely, in part because climate and disturbance vary from year to year. Just as precipitation patterns dictate that only certain years are favorable for the successful establishment of native annuals and perennials, so also may this be true for the spread of brome grasses. Moreover, there is general agreement that disturbance of any kind tends to allow brome grasses to increase in density and distribution. Thus, damage to salt desert shrubs during fires (West, 1994) or root dieback (Harper et al., 1996) after the 1983-84 El Niño event may have enabled *B. tectorum* to greatly expand within some salt desert shrublands.

Case Studies of Escalating Brome Dominance

Three examples will serve to illustrate the importance of long-term monitoring of brome grasses within the GSENM:

■ Desert Experimental Range

In the salt desert shrublands of the Great Basin Desert to the northwest of the GSENM, plant communities have been monitored, though not continuously, since 1935 on the Desert Experimental Range (Harper et al., 1996). Cheatgrass was first noted on the plots in 1958, but was uncommon on the monitored plots that year, occurring in just 0.1 percent of 480, 2- x 5-foot subplots. Less than 40 years later, in 1995, *B. tectorum* was widespread throughout the plots, and particularly so under certain grazing regimes. Under no grazing or low impact grazing, cheatgrass biomass was low compared to biomass in plots under higher impact grazing regimes, particularly under late winter grazing. Although cheatgrass and other alien species continue to reproduce and set some seed in relatively undisturbed stands of native vegetation, invasions of exotics appear to be kept at bay, though perhaps not



indefinitely, in native stands. The well-documented example of vegetation change on Anaho Island, in Pyramid Lake, Nevada, suggests that alien annuals could eventually replace natives even in well-managed areas of salt desert shrublands (Tausch et al., 1994b).

■ Nevada Test Site

Hunter (1990 and 1991) summarized the trajectories of brome grass populations at the Nevada Test Site in the lower elevations of the Mojave Desert (*Bromus rubens* L., mostly <5,000 feet) and the higher elevations of the Great Basin Desert (*Bromus tectorum* L., mostly >4,000 feet). Red brome appears to have invaded the Mojave Desert sometime during the 1920's, although it remained uncommon until after 1950. By the early 1960's, it was abundant at elevations of 4,000-5,000 feet, though it was infrequent in stands of *Larrea tridentata* (creosote bush) at lower elevations. In the late 1980's, it was ubiquitous below 5,000 feet and most common in areas disturbed by small mammals. Between 1972 and 1988, *B. rubens* increased from ~10 percent of ephemeral biomass to 97 percent on a set of plots where biomass was sampled. Similar increases were seen in cheatgrass. Although densities were still sparse in the mid-1960's, the species had become common by the early 1980's, and it existed in almost monoculture patches in some of the large disturbed areas resulting from aboveground nuclear explosions (elevation <5,000 feet). By the late 1980's, *B. tectorum* was widely distributed, reaching in excess of 1,000 individuals per m² in many places, particularly at elevations ranging from 4,240-4,350 feet). Cheatgrass was distributed more patchily than red brome, and was more strongly associated with disturbance. Overall, both of these introduced annual grasses greatly increased in density and frequency over just a 30-year period beginning in the 1950's.

■ Virginia Park, Needles District of Canyonlands

The most recent example comes from an area nearer to the GSENM, and also on the

Colorado Plateau. Despite widespread habitat conversion by *B. tectorum* in parts of the Needles District of Canyonlands National Park and surrounding agricultural lands grazed by livestock, ungrazed Virginia Park remained largely free of cheatgrass except in a few isolated patches until 1995, when it suddenly accounted for up to 90 percent of the cover in some samples (Harper and Kleiner, 1972; J. Belnap's unpublished data). The previous resistance of Virginia Park to invasion had been attributed to the lack of grazing here. Despite this historic absence of anthropogenic disturbance, climatic events unique to that spring (extremely frequent, though light, precipitation that prevented soils from drying out) allowed *B. tectorum* to emerge as a serious pest. Other very wet years in the early 1980's had not produced a similar effect. The reasons for the sudden emergence of cheatgrass in 1995 remain mysterious, since cheatgrass is often said to lack a substantial seed bank. Nevertheless, some studies have shown carryover of viable seed to the second autumn after seed production (Young et al., 1969; Hull and Hansen, 1974). At Virginia Park, healthy cryptobiotic soil crusts may have stabilized sediments so no loose sediment was available to provide the shallow soil cover needed for *Bromus* seeds to imbibe and germinate (J. Belnap, pers. obs.). It is also possible that frequent light rains favor *Bromus*, whereas less frequent heavier rains favor species with deeper root systems (Hunter, 1991). If so, then root dieback in deeply rooted native shrubs and grasses might have enhanced the relative competitive ability of cheatgrass. Whatever the reason for the sudden surge in cheatgrass abundance at Virginia Park, the site's recent history cautions that perpetual vigilance is warranted in any area to which brome grasses have access.

Spanning a diversity of biotic provinces, habitats, and soil types, these examples and others (e.g., the dominance of cheatgrass at Little Sahara dunes in west-central Utah) illustrate the remarkable ability of brome grasses to gain dominance under a wide range of circumstances. Together, they tell us



that low densities and patchy distributions of cheatgrass cannot wisely be viewed as innocuous additions to native habitats. Rather, wisdom born of experience dictates that they be seen as a possible early step in the conversion of these ecosystems. At this stage, it is simply not possible to dismiss such threats out of hand. Failure to monitor and address the problems early on could have serious consequences at some later date.

Why Progressive Ecosystem Conversion?

What factors account for the sudden increase in cheatgrass in Virginia Park and the steady conversion of native shrublands and grasslands to impoverished communities of exotic annual grasses? Although we cannot yet answer this question, a number of hypotheses have been suggested.

Increasing Local Adaptation and/or Phenotypic Plasticity

Important unknowns in studies of invasions of exotic species are how the patterns of genetic variation (within families, and within and among populations) affect the likelihood that invaders will become naturalized, and the extent to which range expansions are accompanied by genetic population differentiation and/or an increase in phenotypic plasticity. One factor that may oppose local population differentiation in *B. tectorum* is selfing, which precludes genetic recombination. Despite cleistogamy in cheatgrass, studies of both electrophoretic and quantitative traits have discovered relatively high levels of within- and between-population variability, due in some part to multiple introductions from genetically distinct populations (Pyke and Novak, 1994). At least some of the significant genetic variation detected in the introduced range appears to be adaptive. Apparently adaptive variation occurs with respect to such traits as flowering

time, net reproductive rate (Rice and Mack, 1991b) and various aspects of seed germination (Beckstead et al., 1996; Meyer et al., 1997). Evidence for adaptive variation is especially apparent in comparisons between extreme environments, where there are general and predictable habitat differences. In contrast, some populations at more moderate sites seem not to be locally adapted. This observation suggests that limited dispersal may restrict the gene flow necessary for populations to become locally adapted (Rice and Mack, 1991b).

A second factor that can oppose local population differentiation is phenotypic plasticity, which can oppose selection for population differentiation by reducing the correlation between genotype and the phenotype, on which selection acts. Temporal and spatial environmental variation in fitness do appear to prevail over genetic determinants of fitness for many traits (Rice and Mack, 1991b). However, Rice and Mack (1991b) note that considerable environmental variability, coupled with the extraordinary phenotypic plasticity of cheatgrass, may shield populations from selection, resulting in the loss of genetic diversity. By this hypothesis, genetic variation and phenotypic plasticity would not be alternative strategies, but components of a single strategy. Evolution of reaction norms (phenotypic latitudes associated with particular genotypes) may also be key to the success of cheatgrass (Rice and Mack, 1991a). Still unknown are what aspects of the biology of cheatgrass are unique and therefore likely to account for its success in invading native communities.

Finally, although outcrossing has been thought to be rare (Novak, 1994; Pyke and Novak, 1994), it may occur occasionally. J.A. Young (pers. comm.) has noted anthers exerted and shedding pollen on cheatgrass plants in naturalized populations within the western U.S. in very wet years, and his observations suggest a mechanism by which adaptive genetic combinations may increase through time.



Gradual Alteration of Soil Nutrient or Microbial Properties

Recent and unpublished studies are suggesting that cheatgrass and other exotics can modify abiotic and biotic components of soils. Thus, M. Miller and J. Belnap (unpublished data) are finding evidence for fine-scale patchiness in soil nutrient status in relation to the past and present distributions of cheatgrass. Previous work has shown that soil chemistry and plant root cation exchange capacity (CEC) can influence distribution and tissue content of higher plants (Crooke and Knight, 1962; Pedersen and Harper, 1979; Woodward et al., 1984). High potassium:calcium ratios, measured in 24 m² quadrats in 1969 in Virginia Park, predicted areas of cheatgrass invasion 26 years later. Moreover, relative to other cations, potassium levels gradually increased through time in patches of *B. tectorum*, but not in control plots without this alien weed. Experimental addition of potassium also favored cheatgrass, and increased levels of potassium in soils were reflected in tissue levels of native plants. The highly charged roots of *Bromus* attract magnesium and calcium in preference to potassium, so that in soils with low total K, or low K:Mg or K:Ca ratios, cheatgrass does poorly. However, once *B. tectorum* establishes, it mines K from deeper soils, and deposits it in litter at the soil surface. (See also Harper et al., 1996, for chenopod annuals concentrating sodium in surface soils by a similar mechanism.) Phosphorus levels also increase under cheatgrass (by an equivalent of 65 kg/ha/yr), possibly by the same mechanism (Rawlings et al., 1997). In contrast, total soil nitrogen can remain the same, while nitrogen mineralization potential can drop by as much as 80 percent (Rimer and Evans, 1997). As litter production increases, cation exchange capacity rises in the soil, and this change favors plants that, like *Bromus* and other annuals, have high root CECs (Woodward et al., 1984).

Other recent data are showing that soil microflora and microfauna are altered in cheatgrass stands. J. Belnap and colleagues

have seen high ratios of fungi to bacteria, as compared with stands of native bunchgrasses. Overall, the abundances of fungi, bacteria, nematodes, and microarthropods are reduced by orders of magnitude. Interestingly, experimental reduction of microorganisms by methyl bromide fumigation of soils from beneath stands of other exotics (*Halogeton glomeratus* and *Salsola pestifer*) has been found to enhance the establishment of native perennials (Harper et al., 1996).

Enhanced Competitive Ability After Disturbance

Native plant communities often keep introduced *Bromus* at bay, though it is difficult to know whether this state can persist indefinitely in the absence of disturbance. Brome grasses and other alien plants are most likely to invade after either natural or anthropogenic disturbance (Harper et al., 1996). In addition to disturbances by livestock, road construction, and improvement, etc., natural disturbances like fires, floods, and habitat alteration by native animals can also contribute to cheatgrass increase (e.g., Hunter, 1991; West, 1994; Harper et al., 1996; Mull and McMahon, 1996). Well-adapted to fire, cheatgrass often dominates plant communities after burns (Wright and Klemmedson, 1965; Young et al., 1969).

Whatever the source of disturbance, cheatgrass appears to excel at preemptive competition for space and resources, perhaps especially when water is relatively abundant (Hunter, 1990). Afterripened seeds germinate readily under a range of conditions of temperature and moisture (Allen et al., 1995; Beckstead et al., 1996; Meyer et al., 1997), and seedlings establish in the fall, in advance of other species. Plants rapidly put down extensive root systems (Aguirre and Johnson, 1991), and with their annual life history, are reproductive years before native perennials can recruit from seed. Experiments in northern Nevada indicate that, after fire, *B. tectorum* competes effectively with native perennials for soil water (Melgoza et al., 1990). Both the productivity and water status of native shrubs were negatively affected



for an extended period of time by cheatgrass. Access to water may also enable brome grasses to preempt the nutrients released by fire or other processes (Maron and Connors, 1996). However, the types of mechanisms contributing to resource preemption are poorly known at present. At least some *Bromus* species with cool season growth apparently enhance their competitive ability by either luxury uptake of nutrients or early season nutrient uptake followed by long-term storage (Hetrick et al., 1994). Also, the depletion of vesicular arborbuscular mycorrhizae in disturbances colonized by bromes may limit the recovery of many native perennials (Wicklow-Howard, 1994). The brome grasses themselves are facultatively mycotrophic.

Precautions for the New National Monument

The information we currently have on invasions of brome grasses specifically, and on introduced plants in general, is sufficient to deduce some likely future trends, and to suggest some possible management and monitoring strategies.

Active Monitoring and Management Against Brome Grasses

Given the threat posed by brome grasses in the GSENM, some form of active monitoring and management should take place. The current patchy distribution makes the problem amenable to active management by herbicides, such as Round-Up. With only modest effort, monitoring could be done in such a way as to define source areas, where local populations are self-sustaining, and sink areas, where population persistence depends on immigration (Figure 1). Removal efforts could then be concentrated in source areas.

Road Restrictions

Increased popularity and use of the new Monument will bring more vehicles and hikers,

both of which can contribute in a major way to the spread of weeds. Both the improvement of existing roads (especially grading of roadside ditches) and increased usage of existing roads (improved and unimproved) are apt to aggravate invasions of brome grasses and other exotic plants by creating new dispersal corridors. The invaders, possibly including new genetic variants, are then poised to expand outward from these corridors, especially during wet years. There is some evidence that restricting travel along existing roads can protect habitat from weeds. Thus, along the sides of multiple existing roads studied by Hunter (1990), introduced species (including not just brome grasses, but also *Erodium cicutarium*, *Salsola* spp., and *Sisymbrium altissimum*) dominated all but the route that had been closed to traffic and left undisturbed for many years prior to censusing. With this background in mind, management against alien plants should include closure of roads in remote, lightly infested areas; keeping road improvements to a minimum; and banning the construction of new roads altogether. Scientific access could be permitted, on a limited basis, to roads closed to the general public.

Educational Programs

At other National Monuments and Parks on the Colorado Plateau, programs have effectively educated tourists to avoid walking, riding mountain bikes, etc., on cryptobiotic soil crusts. Not just in the GSENM, but also in these other Parks, similar efforts should be mounted to educate visitors about the threats that weeds pose to native plant communities and to recreational values. Visitors should be informed of the need to monitor clothing, shoes, and tents, so as to avoid dispersing seeds of noxious weeds, and to be extremely cautious with fire during summer and fall. Efforts to educate visitors about the values of cryptobiotic soils may also be useful in preventing invasion of these areas by brome grasses. Once disturbed, these crusts are slow to recover, and cheatgrass seeds appear to penetrate the disturbed areas more readily than they do intact crusts (J. Belnap, unpublished data). If this is so, then preservation of crusts is important for

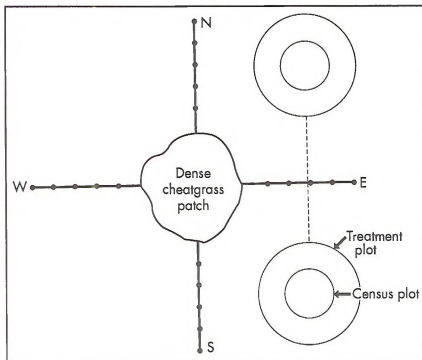


Figure 1. A scheme for both monitoring the spread of *Bromus tectorum* from patches of high density and distinguishing self-sustaining source populations from sink populations, dependent on immigration. Along the four cardinal compass directions, and at regularly increasing densities from a patch, control and cheatgrass removal plots (much enlarged here) are established and monitored yearly in late spring (treatments assigned randomly between the two plots at each distance). Invasions of the brome grass into adjacent habitat could be detected by comparing relative densities across distances and years. Significant differences might be expected among compass directions if the predominant wind direction affects seed dispersal. Immediately after late spring censuses, cheatgrass is removed on treatment plots by cutting plants off at ground level, so as not to cause soil disturbance by pulling up plants by their roots. Cut plants should be allowed to remain where they fall, so that nutrients will be returned to the soil. Census subplots should be somewhat smaller than removal plots and centered in the latter plots, so as to measure relatively long-distance dispersal, rather than dispersal from immediately adjacent sites. Comparisons of *B. tectorum* densities on removal and control plots in each year after cheatgrass removal allow determination of the extent to which populations are derived from the plot itself, versus from immigration by seed dispersal from source areas nearby. If cheatgrass densities in removal plots are substantially lower than in control plots on the year following cheatgrass removal, then the local population would be judged self-sustaining. However if, at some particular distance along the transect from the patch, there ceases to be a substantial difference between densities on treatment and control plots, then populations at that threshold distance and subsequent distances may be deduced to be sink populations, the existences of which are dependent on immigration. Management strategies for controlling cheatgrass with herbicides or other treatments might then be limited to source areas only.

reasons other than erosion control and nitrogen inputs to ecosystems (see, e.g., Harper and Marble, 1988; Evans and Ehleringer, 1993).

the interspaces among bunch grasses. Like cheatgrass, galleta grass also competes best on soils with some clay content and higher CECs than sandy soils. Disturbances on sandy soils

Habitat Restoration After Fire

Both natural and anthropogenic fires, if they are sufficiently hot to kill native grasses, can open up environments to dominance by exotic plant species, especially cheatgrass. It is crucial then to begin restoration efforts immediately. The temptation is to plant nonnative crested wheatgrass (*Agropyron cristatum*), which competes well with cheatgrass and provides good forage for cattle. However, crested wheatgrass also forms dense, monodominant stands with little interspace for native species (Marlette and Anderson, 1986). These monocultures can also be unstable; large die-offs during drought years can again open up the habitat to invasions by exotic species (S. Monsen, pers. comm.).

Inside a National Monument, management should not favor cattle forage over native biodiversity. Thus, it is crucial to develop alternatives to crested wheatgrass. Such alternatives might include, for example, galleta grass (*Hilaria jamesii*) and squirreltail (*Elymus elymoides*). Like cheatgrass, the latter species does well after fire (Blank et al., 1994). The former species, which has C_4 photosynthesis, competes well with cheatgrass, a C_3 species, even where *Bromus* still grows in



might be replanted with native species of *Oryzopsis* (ricegrass), *Stipa* (needlegrass), or *Sporobolus cryptandrus* (drop seed). Efforts should always be made to replant with appropriate natives, which are available from companies specializing in their collection.

Chaining

In places, intensive grazing and/or fire suppression are documented to have contributed to unnaturally high densities of woody perennials like *Juniperus* spp. Because dense associations of juniper can increase the likelihood of hot fires, land managers often promote the use of chaining, followed by localized burns of slash. However, this strategy can backfire, since dense juniper stands often lack a viable seed-bank of native grass species, and because chaining can disturb soil crusts and increase soil surface roughness to favor cheatgrass germination (Tisdale and Hironaka, 1981). Chaining is not recommended unless there is both strong evidence for unnaturally high juniper densities and a commitment to revegetate immediately with native species.

Reductions of Brome Grasses in Late Spring and Early Summer

The growth phenology and life history of cheatgrass may promote its success in preemptive competition (see above), but these same attributes make it susceptible to management by late spring or early summer removal (reviewed in Vallentine and Stevens, 1994). Germinating in the fall, *B. tectorum* takes advantage of autumn and winter moisture to establish and develop an extensive root system. By the time many native species initiate their seasonal growth, cheatgrass is large enough to outcompete the natives. In about mid-June, when the habitat has dried substantially, the annual cheatgrass flowers and sets seed. Seeds are dispersed shortly afterward, and the vast majority of the present year's seeds germinate in the subsequent fall. Thus, reduction of cheatgrass biomass in early June would be expected to eliminate much of the subsequent

year's population. Reductions earlier in the year would not be so useful, since spring moisture could allow cheatgrass to compensate for biomass reduction and reproduce, albeit at a somewhat reduced level (Tausch et al., 1994a).

Some investigators have proposed that an early summer grazing regime could be used to hold back cheatgrass invasions (reviewed in Vallentine and Stevens, 1994). Removal of brome grasses by livestock in early June, just as reproductive investment begins, may greatly reduce seed production 1 month later, without the risk of cattle transmitting cheatgrass seeds to less infested areas. Moreover, since most seeds germinate in the year of their production, any grazing-imposed reduction in cheatgrass is likely to occur for several years.

Although at first glance, early summer grazing appears to be a useful strategy for controlling brome grasses, the strategy fails under closer inspection. First, dense patches of cheatgrass are usually surrounded by native vegetation, which the cattle favor. Differential grazing on the natives imposes additional stress on these plants, which then are disadvantaged in competition with cheatgrass (Young and Tipton, 1990). Tisdale and Hironaka (1981) and Tausch et al. (1994a) found that simultaneous and equivalent clipping of cheatgrass and native perennials was more stressful to natives than to cheatgrass. Second, since seedling establishment in *B. tectorum* is favored by rough microtopography (Young and Evans, 1973; Tisdale and Hironaka, 1981), trampling of fragile soil crusts by livestock may lead to increased seed germination and higher cheatgrass densities (DeFlon, 1986). Finally, livestock may disperse cheatgrass seeds, either externally or internally, the latter allowing undigested seeds to be passed in droppings that provide a rich accumulation of nutrients (Vallentine and Stevens, 1994). Considering all of these potential negatives of grazing, heavy late spring grazing of cheatgrass should only occur in large patches where high population densities pose a serious threat, and then only if cattle can be contained to an area where natives are not in jeopardy. In such cases, natives should



be planted soon after removal of cheatgrass. Recommended as an alternative to late summer grazing are herbicide treatments of dense patches of brome, e.g., by Round-Up.

Funding for Basic Science

Plants form the matrix in which all organisms in the new Monument live, and thus, protecting native plant communities is key to the ecological integrity of the GSENM. At present, our ability to protect these communities is greatly restricted by the preliminary nature of our knowledge of processes underlying ecosystem conversion to exotic annuals. Substantial and ongoing funding for scientific research will be absolutely essential to devising means of eradicating or holding in check populations of invasive plants here and elsewhere in the Intermountain West. Among the most promising of control mechanisms are natural disease organisms, principally fungi (Mack and Pyke, 1984; Grey et al., 1995; Groppe et al., 1995; Turnbull and Gossen, 1996; Boyd and Carris, 1997) and rhizobacteria (Mazzola et al., 1995; Gealy et al., 1996). However, until biological or chemical control agents are developed and approved, it is important to contain the spread of brome grasses, to the extent possible, in order to maintain the health of native species. Our recommendations are directed toward that goal.

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Grasshopper Communities in Native and Nonnative Grasslands of the Colorado Plateau: Differences in Density and Species Composition

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ABSTRACT

■ Control of exotic species is becoming a critical resource management issue, especially in areas set aside to protect native species and natural communities, such as National Monuments. If we are to restrict the impacts of exotics, we must understand how they interact with native species and apply this knowledge to reduce their impacts. Thousands of hectares of grassland on the Colorado Plateau, including parts of the Grand Staircase-Escalante National Monument, are dominated by nonnative grasses. Dominance does not depend on continued disturbance; some areas protected for over 30 years are still covered with exotic species. Increased herbivory on remaining native species may contribute to continued dominance after the disturbance has ceased. A shift to nonnative grasses affects quality, quantity, and timing of available food for insect herbivores such as grasshoppers. Pressure on native perennial grasses probably increases, but very little is known about mechanisms or consequences of these changes.

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I conducted surveys of grasshopper density and community composition in native perennial and nonnative annual or perennial grasslands across southern Utah in June and July 1997. Densities in native grasslands were significantly lower than in nonnative grasslands in June; results were mixed in July. There were differences in relative abundances of species between the three kinds of grasslands surveyed. These surveys are part of a preliminary investigation into interactions between grasses, insect herbivores, and insectivores on the Colorado Plateau. Results of the surveys will be presented, and future studies, as well as how understanding these interactions can help in our efforts to control exotic grasses, will be discussed.

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The Bees of the San Rafael Desert: Implications for the Bee Fauna of the Grand Staircase-Escalante National Monument

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Endemic plants of the Intermountain Region reach their greatest diversity in the Canyonlands section of the Colorado Plateau in southeastern Utah. The high rate of endemism is likely due to the section's age and relatively undisturbed isolation. Mountainous barriers surround the Canyonlands except for two gaps: one in the southeast, between the San Juan and Rio Grande Rivers, and another at the Dixie Corridor, a relatively low-lying area between the Grand Canyon and the Utah Plateau, which connects with the Mojave Desert (Cronquist et al., 1972).

Such isolation and plant endemism likely play a role in fostering the endemism of other taxa

ABSTRACT

■ The Colorado Plateau appears to be a region of rich bee diversity and endemism. A 15-year study of the bee fauna of southeastern Utah's San Rafael Desert, a small portion of the Plateau dominated by sand dunes, recorded 49 genera and 333 species—more genera and nearly as many species as in all of New England. Endemism is very high (one-fourth of the species). Diversity is the result of such factors as floral specialization (at least one-third of the species specialize on plants at the family or generic level), abundant and diverse nesting sites, strong seasonality of solitary species, and the historical contributions of diverse sources. Limited sampling in the Grand Staircase-Escalante National Monument suggests it to be equally diverse, but distinctive; nearly half of the Monument's bees are not present in the San Rafael Desert.

in the Canyonlands. Bees, for example, in their mutualistic association with flowering plants (Roubik, 1989), have exchanged pollination services at flowers for plant resources: all the dietary requisites of bees, such as nectar and pollen, and habitation and nest construction materials for some, are obtained from plants. It is little wonder then that many students of pollination and bee biology have long suspected that bee diversity and speciation is determined, in part, by angiosperm diversity (Neff and Simpson, 1993). For this reason alone, we would expect high endemism among the Canyonlands' bees and a general diversity that reflects that of plants. In addition, the Canyonlands are expected to support a unique and rich bee fauna because it is arid: this large area of southeastern Utah averages but 12.7–20.3 cm of precipitation per year. It is well-known that many desert areas are especially rich in endemic bees, probably because the incidence of some of the enemies of bees (e.g.,



fungi) are lower there, and opportunities for specialization on flowers are higher (Michener, 1979).

Prior to 1979, information on bee diversity on the Colorado Plateau was rudimentary. Little survey work had been conducted, and only a handful of species, mostly widespread and common elsewhere, were known from the region. In the summer of 1979, personnel from the USDA Agricultural Research Service Bee Biology and Systematics Lab (BBSL) made their first expedition to the Canyonlands, to the poorly known San Rafael Desert (SRD). The promising results of that expedition led to repeated trips over the next 15 years.

The SRD lies at the heart of the Colorado Plateau. Surrounded by regions of spectacular topography—the San Rafael Swell, Arches National Park, Canyonlands National Park, the Henry Mountains, and Capitol Reef National Park—the SRD presents a contrasting, pedestrian landscape, with only a few scattered buttes and monuments accenting a largely flat terrain. This region, also known as the Green River Desert (Stokes, 1977), ranges in elevation from 1300 to 1800 meters and is marked by extensive sand dunes. Much of the average precipitation (13.3–15.3 cm) comes in late summer and early fall and produces a flora distinctive from that appearing in spring. Summers are hot; average temperatures in July are 27 °C, and many days the maximums exceed 38 °C. The predominant vegetation is galleta three-awned shrubsteppe (Cronquist et al., 1972).

Here we present results of our survey of the bee fauna of the SRD and discuss the implications for other portions of the Colorado Plateau such as the Grand Staircase-Escalante National Monument.

Methods

Collections of bees on the SRD were made as time permitted by various personnel from the BBSL between 1979 and 1993. Most collections were made with insect nets at flowers, but also at nesting and resting spots, while walking through favorable habitat. As a measure of collecting effort, we used the number of collector-days, where a collector-day is a single day's activity by 1 person who captured at least 20 specimens. We tallied 182 collector-days spread across the flight season for bees from April through October, but with collecting effort concentrated in late spring, midsummer, and early fall (Table 1). More than 13,000 specimens were collected as part of trapnesting studies (Parker and Bohart, 1966), and a few were collected in malaise traps. Specimens were mounted, identified, given unique accession numbers, and entered into a computer database. Specimens are deposited in the U.S. National Pollinating Insects Collection, Logan, Utah.

Results

As anticipated, we found the bee fauna of the SRD to be very rich in bee endemics. We also found it to be very rich in the total number of bee species: 333 species were collected including all of the families and nearly half (41 percent) of the genera known from the United States (Table 2). Except for the well-known honey bee (*Apis mellifera*), which came to the Americas with European colonists early in the 17th century, all are native to North America. The fauna represents 9 percent of the 3,959 species and subspecies known from the continental U.S. in an area of only 0.05 percent of the continental land mass. One-fourth of the species are endemic to the Colorado Plateau and most of these are presently known only from the SRD.

Table 1. San Rafael Desert collecting effort by half month (number collector-days*).

Apr early	late	May early	late	June early	late	July early	late	Aug early	late	Sept early	late	Oct early	late	Total
3	7	14	16	27	2		31		40	15	25	1	1	182

* Collector-day = One person's activity for 1 day with a minimum of 20 specimens collected.

**Table 2.** The bee fauna of the San Rafael Desert.

Family	Subfamily	Genus	Species	New Species	Number of:				
					Endemics	Hat Desert Disjuncts	Great Plains Disjuncts		
Colletidae	Colletinae	<i>Colletes</i>	13	1	1	3	1		
	Hylaeinae	<i>Hylaeus</i>	7	3	3				
Halictidae	Rophitinae	<i>Dufourea</i>	2	1	1	1			
	Nomiinae	<i>Nomia</i>	3			1	1		
	Halictinae	<i>Agopastemon</i>	4						
		<i>Diolictus</i>	22						
		<i>Evyloeus</i>	5				1		
		<i>Halictus</i>	4				1		
		<i>Lasioglossum</i>	1						
		<i>Sphecodes</i>	7						
		<i>Sphecadagastro</i>	3			1	1		
Andrenidae	Andreninae	<i>Ancylandrena</i>	1		1				
		<i>Andreno</i>	25	3	6	4	3		
	Panurginae	<i>Collopsis</i>	5	1	1	2	1		
		<i>Heterosarus</i>	2	1	1				
		<i>Panurginus</i>	1		1				
		<i>Perdita</i>	56	24	36	8	1		
Melittidae	Dasyopodinae	<i>Hesperapis</i>	4	2	2				
Megachilidae	Lithurginae	<i>Lithurge</i>	1						
	Megachilinae	<i>Anthidiellum</i>	1						
		<i>Anthidium</i>	8	1		3			
		<i>Dianthidium</i>	6			2			
		<i>Dioxys</i>	4	1	1	1			
		<i>Stelis</i>	6	1	1	2			
		<i>Caellaxys</i>	5				1		
		<i>Megachile</i>	17		1	1	1		
		<i>Atoposmia</i>	2	1	1	1			
		<i>Ashmeadiella</i>	13	1	1	5			
		<i>Haplitis</i>	5		2	2			
		<i>Osmia</i>	14	2		5	1		
		Apidae	Namadinae	<i>Epeolus</i>	1				
				<i>Halcoposites</i>	1				1
				<i>Nealorra</i>	7	2	4		1
				<i>Nomoda</i>	12	1	1		2
				<i>Tripeolus</i>	8				1
			Xylacapinae	<i>Ceratina</i>	2				
				<i>Xylocapa</i>	1				
Apinae	<i>Anthophora</i>		14	1	1	1	1		
	<i>Habropoda</i>		2			1			
	<i>Diadasia</i>		4						
	<i>Melissades</i>	14			1	1			
	<i>Svostra</i>	3			1				
	<i>Synholania</i>	6			2	1			
	<i>Exomolopsis</i>	2		2					
	<i>Xeromelecta</i>	1							
	<i>Melecta</i>	3	1	1	1				
	<i>Zocosmia</i>	1							
	<i>Apis</i>	1							
	<i>Bambus</i>	3							
Total			333	48	68	50	21		



The bees of the SRD are diverse in size (they range in length from 3 to 25 mm), aspect (they vary in color from those that are black with fuzzy light hair, to those with red or yellow markings on the body, to others that are entirely red, blonde, or bright metallic blue or green), and lifestyle (solitary, social, and cleptoparasitic). Unlike the perennial honey bee, which lives in hives containing a queen with many workers, females of the vast majority of our native bees live solitary adult lives of short duration (only a few weeks per year): queens and workers are absent. Our relatively few social species include all of the bumblebees (*Bombus*) and an unknown fraction of the Halictinae in the genera *Halictus*, *Dialictus*, and *Eurylaeus*. Also, unlike honey bees, most native bees do not make honey (bumblebees are the only exception). And, while honey bees collect pollen from a wide array of flower species, many native bees restrict pollen collection to a single family or genus of plants. Twelve genera (17 percent of the species) are cleptoparasites, cuckoo bees who collect no pollen, but whose offspring mature in the usurped cells of other pollen- and nectar-collecting bees. Just as many pollen-collecting bees have specialized foraging habits, most cleptoparasites attack nests of a single host genus.

As might be expected, the numbers of individuals and species collected were positively related to collecting effort. When collecting effort and bee species collected were graphed in temporal sequence, beginning with the first collection in August 1979 and ending with the last collection in April 1993, there was a strong relationship between cumulative

effort and cumulative unique species recorded ($R^2 = 0.96$, $P < 0.0001$, Figure 1). Noteworthy is the absence of any obvious approach to an asymptote: an undetermined number of species remain to be collected. Those times most likely to yield additional, unrecorded species are April, October, the last half of June, and the first halves of July and August (Table 1) because collecting efforts during these periods have thus far been light.

To discern the pattern of seasonal occurrence of bee species, we divided each month into early (days 1-15) and late (days 16 ff.) periods, and tabulated the number of species recorded (Figure 2). Because of uneven collecting effort, the results are intended for illustration only

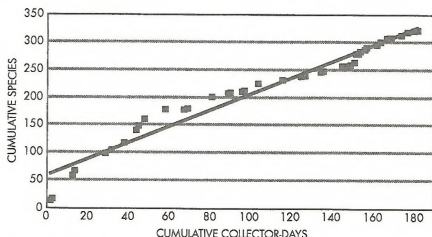


Figure 1. Cumulative number of unique bee species collected from 1979 to 1993 versus cumulative collecting effort. A collector-day is defined as a single day's activity by 1 person who captured at least 20 specimens. The relation is described by the equation: $y = 1.48x + 59.66$. ($R^2 = 0.96$, $P < 0.0001$).

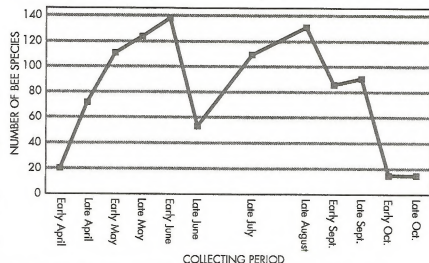


Figure 2. Number of bee species recorded by half month (early = 1-15, late = 16 ff.). No collections were made in early July or early August.



and should be examined with Table 1 in mind. Indeed, there were highly significant correlations between collecting effort and the two dependent variables: individuals collected per half month ($R^2 = 0.91$, $P < 0.0001$) and species collected per half month ($R^2 = 0.71$, $P < 0.001$). As might be surmised, there was also a significant relation between the number of individuals and number of species collected by half month ($R^2 = 0.86$, $P < 0.0001$).

Despite the influence of collecting effort, the data can be used to make several points of interest. First, large numbers of species can be in flight at any given time: we recorded roughly 130 species in 2-week periods in both early June and late August (Figure 2). Second, like some other arid areas, e.g., shortgrass prairie (Tepedino and Stanton, 1980), the bee fauna of the SRD seems organized into two primary peaks, one in spring that culminates sometime in May or June, and another in August. For the most part, all families react in approximately the same manner throughout the bee flight season (Figure 3). While these are also times of peak collecting effort, other times of heavy collecting (late July, late September) do not yield as many species. Thus, the bimodality seems a real phenomenon though the troughs are likely to be less deep when sampling is complete.

The seasonal turnover in the composition of the four major bee families can also be seen through the use of similarity indices (Figure 4). We used Sorenson's Presence-Absence Index (Southwood, 1978) to compare the similarity of the bee fauna of each month with that of subsequent months. (Sorenson's Index is given by: $2A/(B + C)$ where A is the number of species shared between two samples, here months, and B and C are the number of species recorded in each sample being compared.) From the graphs, it is clear that the longer the time between sampling periods, the lower the similarity in the fauna. This is especially true for bees in the Megachilidae, the leafcutting bee family, which generally have the lowest similarity values. Turnover in this family may be great because many species have very selective flower-visiting habits: such species likely cease their adult activity as soon as their preferred floral resources finish blooming. Conversely, the lowest turnover is displayed by the family Halictidae, which is likely to have many primitively social species. Species displaying social behavior use a diversity of flowering plants and fly for longer periods. Thus, they are a more predictable component of the fauna.

It would be instructive to compare the phenology of the bee fauna with that of flowering angiosperms of the SRD. The bimodally distributed bee fauna may track,

albeit roughly, a bimodal distribution of plant flowering diversity (Tepedino and Stanton, 1980). Others (e.g., Kochmer and Handel, 1986) have described plant communities that display bimodal flowering patterns. Unfortunately, we have been unable to locate such data for the SRD. The only list of plants of the area known to us includes all of the San Rafael Swell, but little of the SRD (Harris, 1983).

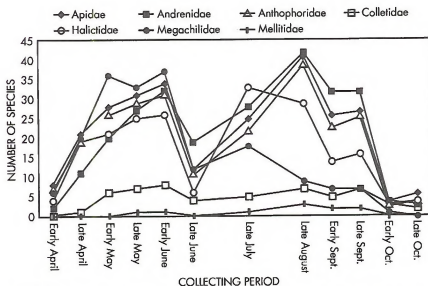


Figure 3. Number of bee species recorded in each family by half month (early = 1-15, late = 16 ff.). No collections were made in early July or early August.

Some (e.g., Linsley, 1958) have suggested that the

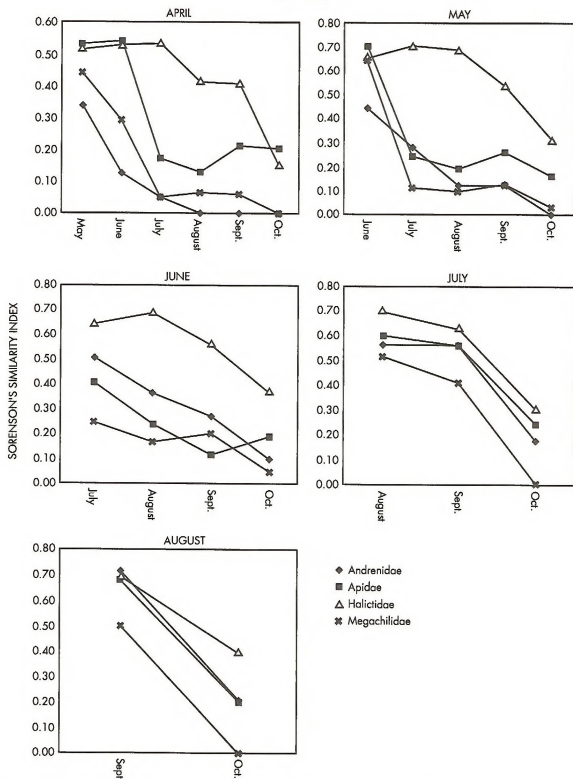


Figure 4. Change in similarity of bee fauna with time for the four most important families. Each graph represents the similarity between the month of note and succeeding months. To calculate similarity, Sorenson's Presence-Absence Index was used.

emergence of adult bees from diapause or quiescence in arid regions is triggered by precipitation: bee species richness might be correlated with precipitation because of the

connection between plant flowering and available moisture. We examined average monthly precipitation data from the two closest weather stations in Hanksville and Green River



(about 80 km apart). Precipitation is highly correlated between the sites (Spearman's $\rho = 0.96$) and the totals differ by only 11 mm. Like the pattern of bee species richness, precipitation is bimodal in the SRD: about 25 percent falls between March and May, and 37 percent falls between August and October. We compared bee species richness using the number of unique bee species collected each month with monthly precipitation. Because we were unsure of the lag between precipitation and bee emergence we conducted correlations for the months April to September [we eliminated October because collecting effort was very low (Table 1)] using several estimates of precipitation: monthly, sum of previous 3 or 4 months, and previous 6-month estimates in two ways—including and excluding the precipitation in the bee sampling month. Only in the latter case did we obtain significant results ($R^2 = 0.61$, $P < 0.05$), and then the relationship was inverse rather than positive. Thus, we were unable to relate bee species richness to precipitation in any simple way.

Preston (1948, 1962) advanced the theory that species abundance distributions of taxa in diverse collections should fit a lognormal distribution. This was thought to be a property of species-rich assemblages where species abundances were governed by numerous independent factors compounded multiplicatively (Whittaker, 1972). Certainly, native bees in the SRD fit this description. Their species abundances do not, however, fit a lognormal curve ($X^2 = 87.1$, $P < 0.001$). The curve deviates from the expected values, particularly in the region of uncommon species (Figure 5). There are

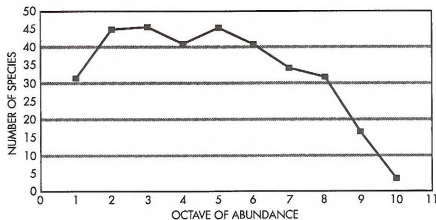


Figure 5. Species abundance data for the entire collection fitted to a lognormal distribution. Each octave of abundance is double the previous one; i.e., Octave 1 = 0-1 individuals/species, Octave 2 = 1-2, Octave 3 = 2-4, etc. The collection does not fit a lognormal distribution ($\chi^2 = 87.1$, $P < 0.001$). See Ludwig and Reynolds (1988) for further details.

fewer uncommon species and more common ones than expected. Whether additional collecting during the time periods that are under-represented will bring the curve closer to lognormality remains to be seen.

How diverse is the SRD compared to other known bee faunas? Such a comparison is hampered first by the paucity of complete local or regional faunas, and second by disparities in geographic size, location, context, and sampling intensity. For example, lower diversity is expected on islands, both physical (Channel Islands) and habitat (Sand Mountain and Blow Sand Mountain) (Michener, 1979). One could also argue that the largely sandy substrates with extensive exposed sandy regions characteristic of the SRD represent a habitat island, as they are surrounded by regions largely devoid of sand. However, the SRD bee fauna is in no sense depauperate. Indeed, it compares favorably with the six other western local faunas available, and with a regional count for New England (Table 3).

Table 3. Diversity of nearctic bee faunas.

	Genera	Species
San Rafael Desert, Utah	49	333
Albany County, Wyoming (Tepedino, 1982)	40	194
Curlew Valley, Idaho/Utah (Bahart and Knowlton, 1973)*	43	340
Sand Mountain & Blow Sand Mountain, Nevada (Rust et al., 1983)	28	59
Maljave National Preserve, California (Griswold, unpub.)	58	305
Pinnacles National Monument, California (Griswold and Messinger, unpub.)	51	316
Channel Islands, California (Rust et al., 1985)	36	154
New England (Mitchell 1960, 1962, Stubblefield and Seger, unpub.)	43	365

*Augmented by pastpublication records.



The SRD has a higher generic diversity than all except the two mainland California sites and greater species richness than all sites but Curlew Valley. There are nearly as many species as in all of New England.

Discussion

What might account for the high diversity and endemism of the SRD bees? Both biological and historical factors likely play a role: floral specialization, an abundance of favorable nesting sites, strong seasonality, and historic contributions from a variety of faunal sources.

Floral Specialization

Bees visit flowers for both nectar and pollen. They frequently visit a variety of flowers for the nectar needed to fuel their own activities. Some bees also have catholic tastes for pollen, the primary source of food (often mixed with nectar) for their offspring. Other bees are much more discriminating in their choice of pollen sources, restricting their collections to a single family or genus of plants. Accurate determination of pollen specialization requires either analysis of pollen loads carried by bees in their "pollen brushes" or of nest cell provisions. We have not conducted such a study, but specialization can be inferred from observations on visitation. Where females consistently restrict their floral visits to particular plant taxa in the presence of other flowering plants at different sites and dates, pollen specialization is likely. Flower visitation records from the SRD suggest that at least one-third of the bees are specialists at least at the family level, with most specializing at the generic level (Table 4). The estimated incidence

of specialization is probably an underestimate given our limited data on visitation. Regrettably, floral visitation was not assessed during the early years of this study.

Some patterns are apparent among specialists. Members of the family Andrenidae (*Andrena*, *Calliopsis*, *Perdita*) are disproportionately abundant among specialist bees. *Perdita*, in particular, accounts for 26 percent of known specialists. By contrast, the Halictidae are poorly represented. All known specialists are solitary bees, as would be expected, given the short

Table 4. Floral specialization in San Rafael Desert bees.

Plant	Bee Genera (Number of species, no number = 1 species, specializing)
Asteraceae	<i>Perdita</i> (7), <i>Calliopsis</i> , <i>Anthaphara</i> , <i>Exomalopsis</i> , <i>Melissades</i> (9), <i>Svastra</i> , <i>Calletes</i> (4), <i>Ashmeadiella</i> , <i>Dianthidium</i> (4), <i>Megachile</i> (3), <i>Osmia</i> , <i>Hesperapis</i>
<i>Chrysanthamnus</i>	<i>Andrena</i> , <i>Perdita</i> , <i>Anthaphara</i> , <i>Melissades</i> (2)
<i>Encelia</i>	<i>Atoposmia</i>
<i>Helianthus</i>	<i>Andrena</i> (2), <i>Perdita</i> (2), <i>Diadasia</i> , <i>Svastra</i> (2), <i>Hesperapis</i>
<i>Malacathrix</i>	<i>Calliopsis</i> , <i>Dufourea</i>
<i>Stephanameria</i>	<i>Perdita</i>
<i>Wyethia</i>	<i>Perdita</i>
Baraginaceae	
<i>Cryptantha</i>	<i>Haplitis</i> (2)
<i>Tiquilla</i>	<i>Perdita</i> (2)
Brassicaceae	<i>Andrena</i> (2)
<i>Lepidium</i>	<i>Calliopsis</i> , <i>Perdita</i>
<i>Stanleya</i>	<i>Perdita</i> (2)
Cactaceae	
<i>Opuntia</i>	<i>Diadasia</i> , <i>Ashmeadiella</i> , <i>Lithurge</i>
Capparaceae	
<i>Cleome</i>	<i>Perdita</i> (2)
Euphorbiaceae	
<i>Euphorbia</i>	<i>Perdita</i>
Fabaceae	<i>Anthidium</i> (2), <i>Haplitis</i> , <i>Osmia</i> (5), <i>Anthaphara</i>
<i>Dalea</i> & <i>Psarathamnus</i>	<i>Calletes</i> , <i>Ashmeadiella</i>
<i>Lolus</i>	<i>Ashmeadiella</i> (2)
<i>Petalostemon</i>	<i>Perdita</i> , <i>Calletes</i>
Hydrrophyllaceae	
<i>Phacelia</i>	<i>Anthidium</i>
Loosaceae	
<i>Mentzelia</i>	<i>Perdita</i> (2)
Malvaceae	
<i>Sphaerolceae</i>	<i>Andrena</i> , <i>Calliopsis</i> , <i>Perdita</i> (4), <i>Diadasia</i> (2), <i>Calletes</i> , <i>Megachile</i> (2), <i>Hesperapis</i>
Onagraceae	
<i>Camissonia</i>	<i>Dufourea</i>
<i>Oenothera</i>	<i>Andrena</i> (2), <i>Anthaphara</i> , <i>Synhalania</i> , <i>Sphecadogastra</i> (3)
Papaveraceae	
<i>Argemone</i>	<i>Perdita</i>
Polemoniaceae	
<i>Gilia</i>	<i>Perdita</i> (2)
Scrophulariaceae	
<i>Cardianthus</i>	<i>Anthidium</i>
<i>Pentstemon</i>	<i>Atoposmia</i>



bloom period of most flowering plants. Small- to medium-sized bees (3-10 mm body length) are better represented than are large bees.

Causes of specialization are difficult to ascertain. Floral characteristics may play a part. Restrictive floral morphologies (Boraginaceae, Fabaceae, *Gilia*, Scrophulariaceae), odd pollen morphologies (*Opuntia*, *Oenothera*), and atypical timing of pollen presentation (*Mentzelia*, *Oenothera*, *Argemone*, *Stephanomeria*) may be important. Most specialists on plants with distinctive flowering times have flight activity patterns timed to synchronize with pollen presentation. Examples include dawn flight of *Andrena linsleyana* on *Oenothera*, early morning activity of *Perdita moabensis* on *Stephanomeria*, and late afternoon flights of *Perdita multiflorae* and *P. holoxantha* coinciding with the blooming of *Mentzelia*.

Specialization on abundant floral resources might be expected. Many of the plants listed in Table 4 are widespread and abundant; others, such as *Camissonia*, *Penstemon*, and *Argemone*, are localized in small populations. Some abundant components of the SRD flora that are attractive to bees, *Astragalus* (Fabaceae), *Poliomena* (Lamiaceae) and *Eriogonum* (Polygonaceae), appear to lack specialists.

Nesting

Bees are known to nest in a variety of substrates and environments. Nests may be excavated in the soil, vertical banks, sandstone cliffs, pithy stems, or wood. Other bees construct exposed nests of resin or resin and pebbles. Nesting biologies of a handful of species from the SRD have been published (Parker, 1984, 1986, Parker and Griswold, 1982, Parker et al., 1986); biological information on a few others remains

unpublished, including the results of trap-nesting studies. The nesting biologies of the vast majority of SRD bees remain unknown. Based on available data from the SRD and studies conducted elsewhere, patterns of nesting can be inferred for the SRD bees (Table 5).

Most bees excavate their nests in the soil. Tunnels are constructed leading to one or more cells, ellipsoids excavated in the soil and often lined with glandular secretions. Each cell is the birthing place for a single offspring. An egg is laid on the provision, the pollen and nectar mass, which provides the nutrients needed for the developing larva. Following egg laying, the female seals the cell and has no further interaction with her offspring. Many species nest shallowly, less than 10 cm below the surface. Others nest much deeper. An excavated nest of *Andrena haynesi* descended to a depth of almost 3 meters (Parker and Griswold, 1982), representing the greatest depth recorded for any temperate zone bee.

Most bees are solitary nesters, constructing and provisioning their nests without the assistance of other bees. These nests may be aggregated, however. Sandy substrates seem to be particularly attractive to many ground nesting bees and dense aggregations have often been observed on dunes and dune margins. In a few instances, multiple females use a common nest entrance, but are assumed to provision

Table 5. Nesting strategies of San Rafael Desert bees.

Excavators	Ground	Colletidae: <i>Calletes</i> Halictidae Andrenidae Melittidae Megachilidae: <i>Anthidium</i> (some), <i>Osmia</i> (few), <i>Megachile</i> (same) Apidae (most)
	Vertical banks	Colletidae: <i>Hylaeus</i> (some) Apidae: <i>Anthophora</i> , <i>Exomalopsis</i>
	Stems & wood	Megachilidae: <i>Lithurge</i> , <i>Haplitis</i> Apidae: <i>Ceratina</i> , <i>Xylacopa</i>
	Renters	Wood cavity Colletidae: <i>Hylaeus</i> (most) Megachilidae (most)
Builders	Soil cavity	Megachilidae (same)
	Cracks in rocks	Megachilidae: <i>Atoposmia</i> , <i>Ashmeadiella</i> (some)
	Surface of stones & stems	Megachilidae: <i>Anthidiellum</i> , <i>Dianthidium</i> (most)



independently. A nest of *Perdita multiflorae*, with at least 23 females, was excavated on a dune margin (Griswold and Parker, unpub.). While the majority of SRD bees appear to prefer sandy substrates, other soils are also utilized. Dense aggregations of *Diadasia* have been observed along seldom-used dirt tracks in hard-packed clay soils. One species of *Anthidium* excavates very shallow nests in friable soils (Griswold, unpub.).

Seasonality

At least as colonies, groups of social bees are long-lived. Honey bees are perennial; nests of *Bombus* and some halictids are active throughout the blooming season. By contrast, the adult lives of most solitary bees are short, on the order of a few weeks at most. They generally have but one generation per year, and thus are, for the most part, seasonally restricted. This results in a marked change in the composition of the fauna which is manifested in bimodality (Figure 4). *Andrena* (8 percent of spring fauna) and Megachilinae (26 percent) are best represented early in the season. During the summer and fall, *Perdita* and *Melissodes* dominate (30 percent of summer-fall fauna). The presence of both spring and summer-fall floras that differ in familial composition may increase bee diversity by effectively increasing the portion of the year with adequate but different floral resources.

Faunal Affinities

The SRD fauna is remarkable for its high rate of endemism. Fully one-fourth of the species are endemic. A handful of these have been described (Parker, 1983, 1985, Griswold and Parker, 1988, 1998, Griswold, 1993, Thorp, 1987); the majority remain unnamed. A number of these species may be more broadly distributed across parts of the Colorado Plateau, but they are unlikely to be present outside this region. Some endemics seem to be replaced in other parts of the Colorado Plateau by sibling endemics. An example is two recently described *Argemone* specialists, *Perdita ute*, presently known only from the SRD, and its sibling *Perdita angellata*, from the southern part of the Plateau in northern Arizona.

The remainder of the fauna shows the influence of diverse source areas. One-fourth of the fauna represents disjuncts either from the hot deserts to the southwest (17 percent) or from the Great Plains and east (7 percent). Most of the remaining species are restricted to the west: widespread in the western United States (21 percent), southwestern including non-desert areas (12 percent), Intermountain Region (7 percent), northwestern (2 percent), and Intermountain to Great Plains (2 percent). Eight percent are transcontinental. Widespread species tend to be social and/or generalists.

The predominant influence of combinations from warmer-weather sources is evident when the fauna is viewed in terms of taxonomic constituents. Genera with apparent desert origins (*Perdita*, *Ashmeadiella*) or higher diversities in xeric regions (*Dialictus*, *Anthophora*, *Melissodes*) predominate, while the contribution of genera of mesic origins (*Andrena*, *Lasioglossum*, *Osmia*, *Bombus*) is limited. For example, numbers of *Osmia* species at mesic sites range from 20 to 34 (Barthell et al. 1997), compared to the 14 recorded from the SRD.

Implications for Other Parts of the Colorado Plateau

Data from other parts of the Colorado Plateau are fragmentary at best. They do hint of diverse faunas across the region. Higher altitude "islands" such as the La Sals, Henry Mountains, Abajo Mountains, Navajo Mountain, and the San Francisco Mountains might be expected to have distinctive faunas with affinities to Rocky Mountain faunas. What little data there is suggests this to be true. Insular montane components not found in the SRD include *Andrena* (20 species), *Osmia* (16), *Bombus* (5), *Colletes* (3), *Hylea* (2), *Megachile* (2), *Anthidium* (2), *Lasioglossum* (2), and *Anthophora* (1). Most of these represent southern outposts of primarily northern species. For example, *Osmia penstemonis* is widespread at higher elevation, mesic sites across the northwest ranging south along the mountains of California, Utah, and Colorado. What is at least a distinctive morph of this



species was recently discovered above treeline in the San Francisco Mountains. One exception to this pattern of northern "mainland" source areas is *Osmia juxta*, which occurs in Pacific states from British Columbia to California and appears to have colonized higher altitude areas of Arizona and New Mexico from the west; it does not occur in northern Utah or the northern Rocky Mountains. *Andrena coconina*, known only from the San Francisco Mountains, hints at an insular endemic fauna waiting to be discovered. When the upper elevations of the San Rafael Swell have been surveyed, they likely will be added to the list of insular regions. Among the handful of records from the Swell are representatives of *Bombus huntii* and several montane *Osmia*.

Bees of the Grand Staircase-Escalante National Monument

Even regions with elevations comparable to that of the SRD likely have dissimilar faunas. An example is the region encompassed by the Grand Staircase-Escalante National Monument (GSENM). There has been extremely limited sampling of the bees of the Monument: 15 collector-days, 20 localities, and less than 1,000 specimens (182, 95, and greater than 13,000 respectively for the SRD). Further, the localities are not representative of the Monument's diversity; almost all are located along the northwest boundary of the monument between Henrieville and Boulder. Nor are collections comprehensive seasonally. The only major collections are in late May, early June, and late summer (late July to late August). There are no spring collections.

Despite these limitations, the GSENM shows signs of comparable diversity and a distinctive bee fauna. There are presently 152 species known from this region, nearly half (46 percent) the number known from the SRD. Several of these represent northern extensions of species previously believed to be restricted to Arizona, New Mexico, and Texas (*Andrena pecosana*, *Trachusa cordataiceps*, *Megachile rossi*, *Heriades timberlakei*, *Hoplitis incanescens*). Thirteen undescribed species are so far recog-

nized in the genera *Hylaeus*, *Perdita*, *Stelis*, *Hoplitis*, *Osmia*, and *Megachile*. Perhaps most significant is the large proportion of the known fauna that is not shared with the SRD. Two genera (*Heriades* and *Trachusa*) and 41 percent of the Monument's bees are not present in the SRD. We suspect at least two causes: faunal components restricted to habitats not present in the SRD (i.e., pinyon-juniper), and an infusion of austral elements from source areas in Arizona. Given the greater habitat diversity and size of the GSENM, we would expect a larger fauna than that of the SRD when the Monument has been adequately surveyed.

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Status of Bats in the Grand Staircase-Escalante National Monument

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There are 986 species of bats in the world, inhabiting every continent except Antarctica. Of the 44 species of bats known to occur in North America, 19 have been reported in Utah (Utah Division of Wildlife Resources, 1997) (Jackson and Herder, 1997) (Table 1). This includes *Eumops perotis*, the largest bat in the United States, recently reported in southern Utah by the authors. Sixteen of the Utah species have been described as occurring in or adjacent to the Monument.

ABSTRACT

■ Bats represent a unique and poorly understood component of the faunal composition of the Grand Staircase-Escalante National Monument (the Monument). Nineteen species of bats occur in Utah, including eight former Federal candidate species and six considered sensitive in the State of Utah. Sixteen of the Utah species have been described as occurring in or adjacent to the Monument. Distribution records of bats in the Monument are rare, primarily due to the remoteness of much of the Monument and the labor-intensive efforts required to capture and identify bats. In 1996, the Utah Division of Wildlife Resources (UDWR), U.S. Fish and Wildlife Service (USFWS), and Bureau of Land Management (BLM), in an effort to inventory bat species within the Monument, initiated a project to develop a catalog of bat echolocation calls. Bats were identified by capturing them in mist nets over open water sources. To minimize any potential bias toward some species and individuals, bat echolocation calls were collected on an Anabat II ultrasonic bat detector interfaced with a notebook computer. Vocalizations were collected coincident with mist netting to provide verification of the species making the calls recorded. In addition, calls were compared with known vocal signatures collected from geographically similar areas. Twelve species were captured in mist nets; all but one were detected acoustically using the Anabat. In addition, three species were acoustically detected that were not captured. Water appears to be a critical factor limiting the distribution and abundance of bats within the Monument. The authors recommend protection and maintenance of water sources for the benefit of all wildlife, studies to monitor population trends of sensitive bat species, and a cave/mine inventory to document the dependence of these species on habitat types which may be impacted through future recreational uses in the Monument.

Rodents are the only order of mammals that exceed bats in number of species (Tidemann and Woodside, 1978), and yet much about bats remains poorly understood. Though general awareness and knowledge of bats has increased in recent years, more about the biology and ecology of bats needs to be determined if the management of bats is to be successful. This is especially true for the bat

**Table 1.** Bat species known/suspected to occur in Utah with habitat and roosting preferences.

Scientific Name	Common Name	Sensitive Status	Habitat	Preferred Roosting Area
<i>Anrozous pallidus</i>	Pallid Bat		DESH, GRAS, PUU, RIPA	R, C/M, B, F
<i>*Corynorhinus townsendii</i>	Townsend's Big-Eared Bat	X	DESH, GRAS, PUU, RIPA, MXCO	C/M, B
<i>*Eptesicus fuscus</i>	Big Brown Bat		DESH, GRAS, PUU, RIPA, MXCO	C/M, B, R, F
<i>*Euderma maculatum</i>	Spotted Bat	X	DESH, GRAS, RIPA, MXCO	R, C/M
<i>†Eumops perotis</i>	Greater Western Mastiff Bat		DESH, GRAS, RIPA	R, B
<i>*Idionycteris phyllotis</i>	Allen's Lappet Browed Bat	X	DESH, GRAS, PUU, RIPA, MXCO	F, R, C/M
<i>*Lasionycteris noctivagans</i>	Silver-Haired Bat		PUU, RIPA, MXCO	F, R, C/M, B
<i>Lasiurus blossevilli</i>	Western Red Bat	X	PUU, RIPA, MXCO	F
<i>*Lasiurus cinereus</i>	Hoary Bat		PUU, RIPA, MXCO	F
<i>*Myotis californicus</i>	California Myotis		DESH, GRAS, PUU, RIPA	C/M, B, R, F
<i>*Myotis ciliolabrum</i>	Small-Footed Myotis		GRAS, PUU, MXCO, RIPA	C/M, B, R, F
<i>*Myotis evotis</i>	Long-Eared Myotis		PUU, MXCO, RIPA	F, R, C/M
<i>Myotis lucifugus</i>	Little Brown Bat		MXCO, RIPA	F, R, B, C/M
<i>*Myotis thysanodes</i>	Fringed Myotis		DESH, GRAS, PUU, RIPA, MXCO	C/M, B
<i>*Myotis valans</i>	Long-legged Myotis		PUU, MXCO, RIPA	F, R, B, C/M
<i>*Myotis yumanensis</i>	Yuma Myotis		DESH, GRAS, PUU, RIPA	B, C/M, R
<i>*Nyctinomops macrotis</i>	Big Free-Tailed Bat	X	DESH, GRAS, PUU, RIPA, MXCO	C/M, R, B
<i>*Pipistrellus hesperus</i>	Western Pipistrelle		DESH, GRAS, PUU, RIPA	R, C/M, B
<i>*Tadarida brasiliensis</i>	Mexican Free-Tailed Bat	X	DESH, GRAS, PUU, RIPA, MXCO	C/M, B, F

Habitat Preference Codes:

DESH - desert shrub
 GRAS - grassland
 PUU - pinyon-juniper
 RIPA - riparian (cottonwood, willow)
 MXCO - mixed conifer (ponderosa pine, Gambel oak)

* Known or suspected to occur in the Monument.

† Not previously reported in the State of Utah.

Roost Preference Codes:

R - rocks (crevices, cliff faces, and ground rocks)
 B - building or other manmade structures
 F - forest trees or snags (follage, cavity, and under bark roosts)
 C/M - cave and/or mines

species present in the Monument, as very little is known about their abundance and distribution. Currently no species of bats have been classified as threatened or endangered in Utah; however, six species have been listed as sensitive due to declining populations and/or limited distribution (Table 1).

Bats use a variety of habitat types for roosting and foraging, with certain species preferring specific habitats and roost sites (Table 1). Roost sites used by bats include caves, mines, rock crevices, trees, lava tubes, and manmade structures such as barns and eaves of buildings. At one time, bat research was limited to the study of cave-dwelling bats or bats inhabiting roosts easily accessible to researchers (Tidemann and Woodside, 1978). With the advent of mist nets and traps, it became possible to capture bats away from roost sites, usually over open water or along foraging flyways.

However, mist netting and other methods for bat capture are likely biased toward particular species and individuals within a species. Furthermore, a given location may not be used every night by the same species assemblage (O'Farrell, 1996).

Electronic acoustic devices, such as the Anabat II bat detector (Titley Electronics, Ballina, NSW Australia), have been specifically developed to record ultrasonic and audible echolocation calls of bats. These devices can be used for inventorying bat species at a given location without the bias associated with mist nets and other trapping methods. Bats produce echolocation calls as a means of perceiving the environment. A bat can determine the size, shape, distance, direction, and motion of an object by "sensing" the way the object modifies the vocal signals reflected back to the bat (Simmons et al., 1975). Because bat calls appear to be



distinctive for each species (O'Farrell, 1996), a bat detector can theoretically be used to determine the species of bats foraging or flying in a given area. Bat vocalizations recorded by a bat detector also provide valuable information about the behavior of bats, and provide access to information about bat ecology (Fenton, 1988). Specifically, information regarding foraging behavior, habitat use, and possibly social interaction can be garnered from bat vocalizations recorded by a bat detector.

Bat vocalizations from some insectivorous bats in the western United States have been characterized by frequency components of calls, duration of call sequences, and patterns of frequency change over time (Fenton and Bell, 1981). This information has provided a basis for species recognition of free-flying individuals (O'Farrell, 1996). O'Farrell (1996) and others have begun the process of collecting vocal signatures for a catalog of bat calls in Arizona. Although vocalizations of bat species known from southern Utah whose vocalizations have been recorded in other areas of the United States, it is important to compile a catalog specific to the bats of Utah to quantify the degree of variation between and among species. Some species possess a repertoire of variable vocal signatures, and it is possible that geographic variation in "dialects" among members of the same species may exist (O'Farrell, 1996).

The Utah Division of Wildlife Resources (UDWR), U.S. Fish and Wildlife Service (USFWS), and Bureau of Land Management (BLM) initiated a project to develop a catalog of bat echolocation calls in the Monument in 1996. This project was part of a multistate effort to develop a catalog of verified bat vocal signatures, including those recorded in the Monument (Jackson and Herder, 1997). The primary objectives of this project were to:

1. Capture bats at a variety of different locations over different types of water sources.
2. Record vocal signatures of hand-released bats using an Anabat bat detector.

3. Record vocalizations of free-flying bats at each capture location and compare the calls to the vocalizations of hand-released bats from this study and bat vocalizations in other available catalogs.
4. Incorporate verified vocal signatures from hand-released and free-flying bats in the catalog of bat vocalizations being compiled for use in species recognition of free-flying individuals in southern Utah.

This report describes the methods used to capture bats for this study and discusses the use of an Anabat bat detector to record vocalizations of captured and free-flying bats throughout the southern portion of the Monument during 1996 and 1997. Copies of vocalizations for six of the bat species detected in the Monument are included in this report. Also provided in this report is a discussion of management issues pertinent to the protection of bat species in the Monument.

Methods

A total of 13 different locations in the Monument were selected for capturing bats during the study (Table 2). Sites were determined as a result of joint consultation among personnel from the UDWR and the BLM in Kanab, Utah. Criteria for selecting the sites included availability of water, evidence of bat activity, and diversity in elevation. A variety of habitat types was encountered during the field seasons as indicated in Table 2. Site elevations ranged from 4,200 feet to 6,160 feet above mean sea level.

Mist nets were used to capture bats at open water sources, including small creeks, rivers, wildlife catchments, springs, seeps, troughs, and stock tanks. Nets were typically stretched across open water, perpendicular to suspected bat flyways, and also to the wind if possible. Where possible, vegetation, rocky outcrops, or other natural features were used as cover for net sets to impede detection by bats, particularly on full moon nights.



Table 2. Locations of bat capture sites with habitat types and bat species captured and/or acoustically detected throughout the Monument.

Site Name and Elevation in Feet	UTM Coordinates	Habitat Code	Date Netted	Species Captured	Acoustically Detected	Method of Verification
Big Horn Sheep Guzzler* 5,200	X475000 Y4125500	DESH	07/14/97	1 MYTH	MYTH PIHE MYU MYCA	HR, COMP COMP COMP COMP
Cottonwood Creek* 4,600	X417967 Y4117024	RIPA	10/08/96	1 PIHE 1 MYU 3 ANPA 2 MYCI 1 MYTH	PIHE MYU ANPA MYTH PIHE	HR, COMP HR HR HR, COMP COMP
Cottonwood Creek Site #1* 4,840	X421200 Y4129310	RIPA	06/18/97	2 PIHE 4 EPFU 1 LANO	PIHE EPFU LANO TABR MYCA	HR, COMP HR, COMP HR, COMP COMP COMP
Cottonwood Creek Site #2* 4,680	X417990 Y4121400	RIPA CLIF	06/19/97	1 PIHE	PIHE TABR EPFU MYVO MYU MYCA LACI LANO NYMA	HR, COMP COMP COMP COMP COMP COMP COMP COMP COMP
Drip Tank Spring* 4,920	X452990 Y4130690	RIPA	06/17/97	16 PIHE 2 EPFU 4 MYCA 4 ANPA 1 MYTH	PIHE EPFU MYCA ANPA MYTH TABR MYU IDPH	HR, COMP HR, COMP HR, COMP HR HR, COMP COMP COMP
Fin Little Spring* 6,160	X394310 Y4115310	PUU	08/07/97	2 PIHE 3 EPFU 2 MYTH 14 MYEV 12 MYVO 1 ANPA 3 MYCA 4 MYCI 1 COTO 3 UNKN	PIHE EPFU MYTH MYEV MYVO ANPA MYCA MYCI	COMP HR HR HR HR, COMP HR HR, COMP HR, COMP HR, COMP
Kitchen Corral Spring* 5,680	X401100 Y4119900	PUU	08/08/97	2 MYEV 1 ANPA	MYEV ANPA PIHE TABR MYCA	HR HR, COMP COMP COMP COMP
Porio River Site #1* 4,740	X415900 Y4122180	RIPA	06/20/97	None	PIHE EPFU TABR MYCA NYMA	COMP COMP COMP COMP COMP
Porio River Site #2* 4,740	X415400 Y4122850	RIPA	08/06/97	3 PIHE 3 EPFU 1 ANPA	PIHE EPFU ANPA TABR MYCA MYCI NYMA	COMP HR, COMP HR
Pink Cove* 6,360	X385690 Y4115500	JUNI	06/16/97	5 EPFU 2 MYCA 3 MYCI 5 MYVO 2 MYEV	EPFU MYCA MYCI MYVO MYEV ANPA TABR MYU	HR, COMP HR, COMP HR, COMP HR, COMP HR, COMP COMP COMP COMP
Smoky Hollow Road* 4,200	X452400 Y4115950	DESH CLIF	10/07/96	1 IDPH	IDPH PIHE MYCI MYU	HR COMP COMP COMP

Whenever possible, bat capture equipment was assembled prior to 20:30 hours. Usually the nets would be opened between 20:45 hours and 21:00 hours and would typically remain open for a minimum of 2 hours. Capture activities would be stopped if an hour lapsed without capturing a bat or in the event of inclement weather such as severe wind or rain. Nets were periodically monitored for bats; however, it was important to remain away from the netting locations as much as possible to avoid discouraging bat activity.

Captured bats were placed in mesh bags or holding buckets for processing. Processing included recording the time of capture, species, gender, reproductive status, ear length, tragus length, forearm length, and weight. In the interest of time, only weight, gender, and reproductive status were recorded for commonly captured species.

An Anabat II ultrasonic bat detector was interfaced with a notebook computer and used to record vocalizations of free-flying and hand-released bats coincident with netting operations. The Anabat station was set up at each site in an open area in the vicinity of the nets, though not so



Table 2 (continued).

Site Name and Elevation in Feet	UTM Coordinates	Habitat Code	Date Netted	Species Captured	Acoustically Detected	Method of Verification
Tibbott Spring* 4,720	X444510 Y4117460	DESH	07/29/97	21 PIHE 7 MYCA 15 MYTH 3 ANPA 1 UNKN	MYCA MYTH ANPA	HR HR HR
Upper Johnson Lakes Canyon* 5,600	X387217 Y4113010	JUNI SAGE	7/30/97	2 EPFU 6 MYVO 5 MYEV 2 MYTH 2 MYCA 1 MYCI 1 UNKN	EPFU MYTH MYCA	HR HR HR
HR - hand-release	COMF - comparison with known recordings					
Habitat Codes:	Species Codes:					
DESH - desert shrub	ANPA - <i>Antrozous pallidus</i>					
RIPA - riparian	COTO - <i>Corynorhinus townsendii</i>					
CLIF - cliff	EPFU - <i>Eptesicus fuscus</i>					
PIJU - pinyon/juniper	IDPH - <i>Idionycteris phyllotis</i>					
JUNI - juniper	LANO - <i>Lasionycteris noctivagans</i>					
SAGE - sagebrush	LACI - <i>Lasiurus cinereus</i>					
	MYCA - <i>Myotis californicus</i>					
	MYCI - <i>Myotis californicus</i>					
	MYVO - <i>Myotis vallonensis</i>					
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	MYEV - <i>Myotis evotis</i>					
	MYCI - <i>Myotis californicus</i>					
	MYTH - <i>Myotis thysanodes</i>					
	MYVO - <i>Myotis vallonensis</i>					
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	MYTH - <i>Myotis thysanodes</i>					



More than 25 hours were expended recording vocalizations of free-flying and hand-released bats with the Anabat. A total of 633 recordings of vocalizations produced by free-flying bats were obtained. Of these, 101 were verified recordings from hand-released bats produced by 11 different species. Vocalizations produced by hand-released and free-flying *Corynorhinus townsendii* were not detected with the Anabat.

The remaining three species detected but not captured during the study, *Tadarida brasiliensis*, *Nyctinomops macrotis*, and *Lasiurus cinereus*, were verified by comparison with known calls from other sources.

Table 2 provides a summary of the number of bats captured at each site by species and those detected with the Anabat. Information regarding

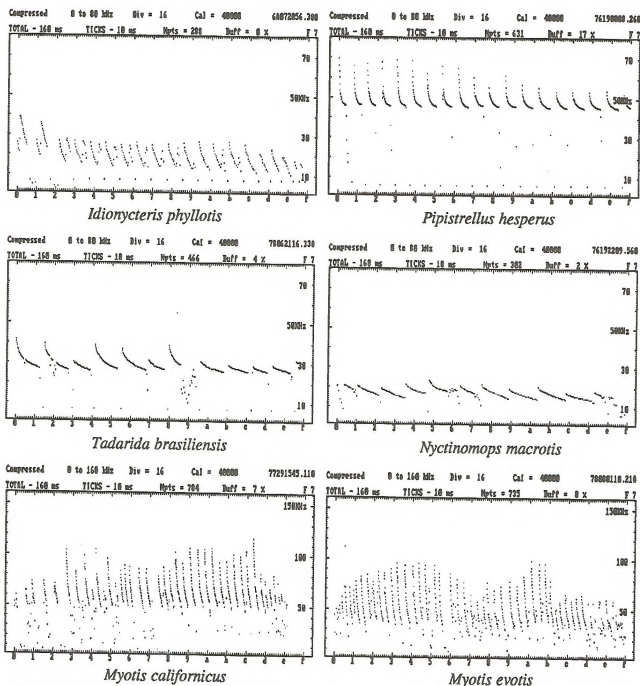


Figure 1. Vocal signatures as recorded on an Anabat II ultrasonic bat detector interfaced with a notebook computer.



each site's location, elevation, and habitat type, as well as bat species detected but not captured is also provided in Table 2.

Hard copy printouts of vocalizations produced by 6 of the 15 species captured and/or detected during the study are provided in Figure 1. Recorded vocalizations were selected for inclusion in Figure 1 based on the species of bat recorded, length and clarity of the call sequence, and overall similarity to previously recorded vocalizations (O'Farrell, 1996). All of the recorded vocalizations included in Figure 1 were results of hand-releases with the exception of *Tadarida brasiliensis* and *Nyctinomops macrotis*.

Discussion

Baseline Occurrence Data

The most commonly captured bat species during the study were *Pipistrellus hesperus* (25 percent), *Myotis evotis* (13 percent), and *Myotis volans* (13 percent). Four of the six bat species listed as sensitive by the UDWR were captured and/or detected.

In evaluating the effectiveness of the Anabat versus traditional capture methods for baseline bat inventories, the ratio of bat species captured to those acoustically detected was examined. For any given capture event, bat species could be captured but not acoustically detected, acoustically detected but not captured, or captured and acoustically detected.

The ratio of the total number of bat species that were captured but not acoustically detected to the total number of species captured was 0.27 to 1. This implies that for every four bat species captured, one would not be detected by the Anabat. Vocalizations of echolocating bats may have been missed during capture events for a variety of reasons, including discontinuous monitoring of the Anabat and limitations of the system. Occasionally the Anabat could not be monitored continuously during a capture event, such as during times of peak bat activity

where all available personnel were tending mist nets and/or processing bats. This resulted in the loss of an unknown number of vocalization files. The Anabat system records only the sound signal with the highest amplitude; i.e., the bat producing the loudest vocalizations and/or flying nearest to the microphone. Vocalizations perceived by the Anabat as being louder in volume will be displayed by the software at the expense of quieter vocalizations. In this way, species that vocalize at higher amplitudes (e.g., *Tadarida brasiliensis*) will be overrepresented in samples of vocal signatures, while those producing echolocations of lower amplitudes (e.g., *Corynorhinus townsendii*) will be underrepresented or missed. *Corynorhinus townsendii* are difficult to detect because the calls they produce are low amplitude and typically contain gaps or holes (missing frequencies) in vocal sequences.

The ratio of the total number of bat species acoustically detected to the total number of bat species captured was 3.16 to 1. This implies that for every 4 bat species captured, 13 would be acoustically detected with the Anabat system and 1 would be missed. The Anabat increased our ability to detect bat species 2.16 times over traditional capture methods alone. However, it should be recognized that some species may still be underrepresented or missed entirely. These results support the supposition that mist netting and other methods for bat capture are biased toward certain species and individuals within a species. This bias may be due to habituation of bats to their surroundings, making them less wary of nets or traps (Thomas and West, 1989, as seen in Foster et al., 1997); differences in visual acuity among bat species; differences in foraging and watering behavior; and variations in environmental conditions (Kunz and Kurta, 1988). Therefore, the Anabat is a valuable tool for inventorying free-flying bat species, provided the training and experience level of the operator is sufficient to accurately identify bats by their vocalizations.

Generally, for those species for which more than one individual was captured, more females than males were represented in the sample. Overall, more females were captured than



males. This may be due to the proximity of maternity roosts to capture locations or gender-specific habitat partitioning; however, the sample size was insufficient to draw definitive conclusions.

Management Issues

Several management issues essential to the protection of bat species in the Monument arose from this study. Since water sources may be a factor that limits the distribution and abundance of bat species, it is important that many, if not all, of the water sources available in the Monument are protected. This may mean ensuring the availability of artificial water sources such as stock tanks and wildlife catchments. Preservation of riparian areas will also be important. Because little data is available regarding how water sources affect the distribution and abundance of bat species, more studies are needed to promote informed decisionmaking in the Monument's resource planning process.

Recreational use of caves and mines on the Monument will likely increase in the future. A single human visitor to a cave or mine used as a bat maternity roost or hibernacula can be life-threatening to the colony. Permanent closure methods are generally undesirable for the same reason. The use of bat-compatible gates has been shown to be effective at a variety of bat roosts. Human safety needs can be met by installing bat gates constructed of horizontal steel bars that allow ingress and egress for bats and other wildlife.

Conclusions/ Recommendations

In addition to providing a baseline inventory of bat species in the Monument, this study identifies the need to monitor water availability, recreational cave use, and mine closure issues. A cave and mine inventory should be conducted

throughout the Monument to document important roosting sites and the dependence of sensitive bat species on particular habitat types. This inventory should include documenting the location, season of use, and species present at caves and mines throughout the Monument. With this information, the appropriate decisions could be made concerning monitoring recreational use of caves and the most effective methods for mine closure.

This study laid important groundwork for developing an inventory of bat species in the Monument, as well as for contributing to the development of a Statewide vocal signatures catalog. Future work should include a wider range of elevations and habitat types. This study is required to better define the distribution of bat species in the Monument and compile a comprehensive library of vocal signatures. A bat vocal signatures catalog would allow for rapid and accurate assessments of bat species presence and habitat use, provide a means for external cave/mine assessment, permit inventories away from watering holes or roost sites, provide cost savings over traditional net surveys, and minimize trap-related mortalities.

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Population Dynamics and Life History Studies of Toads: Short- and Long-Range Needs for Understanding Amphibian Populations in Southern Utah

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Dry conditions of the arid and desert southwest limit both the number of species of amphibians and their distributions in this area relative to more mesic environments in the eastern and south-eastern United States. For example, Alabama supports about five times as many amphibian species as Utah, which is slightly larger in area (Stebbins, 1985; Conant and Collins, 1991). Nevertheless, even in the driest climates of southern Utah, some amphibians can be found, particularly during snowmelts or after heavy rains, or in natural streams, rivers, ponds, and lakes that allow periodic breeding. Larval amphibians can also be found where manmade catchments have replaced natural water courses or wells have brought water to the surface in artificial ponds or cattle troughs. However, little is known about the population size and

ABSTRACT

■ Most amphibians need water to breed and to resist desiccation, and therefore are confined to rivers, streams, lakes, and ponds; the scarcity of water resources probably also limits the number of amphibian species in most areas of southern Utah. However, these general comments are tentative, because so little is known about the biology of any amphibian species in this area. There is a need to locate existing populations and map their distributions, and to understand enough about their life history to make informed management decisions. We conducted a 2-year intensive study of the Arizona toad, *Bufo microscaphus*, at Lytle Ranch in the Beaver Dam Wash in extreme southwestern Utah. Our findings, to be reported more fully elsewhere, found that only three generations comprise the age structure of this population. Longevity in these toads may be a phylogenetic artifact; a survey of the literature confirms that several other related species also have short lifespans.

structure, fecundity, growth, survivability, mortality, and other life history traits of amphibians in these areas, knowledge that would allow informed decisions to be made relative to their conservation and preservation status. This is particularly true for amphibians in the Grand Staircase-Escalante National Monument.

Compounding this lack of detailed information on amphibian life history traits is the urgency brought on by increasing evidence of declining numbers of amphibians worldwide (Blaustein et al., 1994a), and especially in the western United States (Corn, 1994). Although a part of the problem appears to be due to



thinning atmospheric ozone layers that increase detrimental ultraviolet light on developing aquatic eggs (Blaustein et al., 1994b), and a considerable amount is due to habitat alterations by man, the loss of individuals, populations, and species from many areas is not usually explained by a single factor (Blaustein and Wake, 1995; Sarkar, 1996). Perhaps most worrisome is the evidence provided by Pechmann et al. (1991) and Pechmann and Wilbur (1994) that proposed declines are simply natural fluctuations that have remained undetected because studies were not conducted over long enough periods of time.

Intensive population studies over many years are not only laborious, but also expensive. Seasonal surveys to determine the locations of breeding populations, currently being done in most parts of southern Utah by the Utah Division of Wildlife Resources, are a major priority. Counts of individuals to develop relative abundances among populations and measurements to gain some inferences on size (and perhaps age) structure are also useful. However, census data are limited to describing what the population is like, not why it came to be as it is, or how it may respond to future environmental changes. The latter are important to long-term management options.

We believe that the most useful information to be gathered is the age structure of the population viewed in the context of the phylogenetic position of the species or population. Individuals in populations vary in growth rates, time of maturation, and longevity. Is longevity an adaptive response, and if so, how much change has occurred among lineages of related species? If adaptive responses resulted in variable longevity between populations, then each population would have to be considered differently. But if the pattern revealed that all populations of a species had similar life history traits, then the same considerations may apply to all of them, at least to those that are currently sharing genes to some greater or lesser degree. Finally, is there a valid correlation between longevity among species within a clade and what evidence can be gathered most efficiently to reveal these patterns?

Bufo microscaphus at Lytle Ranch

Our main objective, and the one most important to an understanding of the dynamics of toad populations, was to understand the age-structure of Arizona toads, *Bufo microscaphus*, at Lytle Ranch, along the Beaver Dam Wash in extreme southwestern Washington County, Utah. Beginning in April 1996, we visited Lytle Ranch each week for 26 weeks, capturing toads at night along a 1500 meter transect, traversing both stream zones and adjacent sandy terraces. Each toad was measured for snout to vent length (SVL) to the nearest millimeter, individually marked by toe-clipping, and released at the point of capture. Toes were preserved and used to approximate age by the method of skeletochronology (Hemelaar, 1985). In 1997, breeding was observed for 2 weeks beginning in mid-March. Our results, to be more fully reported elsewhere, are summarized here.

Arizona toads at Lytle Ranch number perhaps 1,000 adult individuals within the study area. The sex ratio, both in total counts and by Jolly-Seber estimates, appeared to be skewed, with one male for every two females. Toadlets at metamorphosis averaged about 16 mm SVL; the largest adult was a female, SVL=96 mm. Adult males located by their calls ranged from 52-69 mm SVL; clasping males ranged from 53-68 mm SVL. Females found clasped by males ranged from 56-75 mm SVL. Breeding in 1997 began on March 12 and ended on March 28. During this time, 227 individual egg masses were counted in a 2-kilometer section of the stream and adjacent, stream-fed pools. Rough counts of eggs per mass yielded an average clutch size of 4,500 eggs. Males continued to call after this time, but no more egg masses were detected. Eggs hatched in 3-5 days; larvae remained immobile for several days before the 3-4 mm tadpoles began to feed. Metamorphosis occurred in mid-June in 1996, but occurred in mid-May in 1997; no tadpoles were found in the breeding areas after these dates.



Monthly plots of SVL versus frequency of observations of newly caught, unmarked toads each month for both years (April-September 1996 and March-September 1997) showed one or two valleys separating two to three peaks that shifted upward each month. The plots suggested three cohorts of growing toads, a newly metamorphosed (first year) group of juveniles (SVL=16-50 mm), an apparent second year group of adults (SVL=50-75 mm), and a possible third year group of adults (SVL=75-96 mm). Growth rates calculated from recaptured marked toads averaged 0.19 mm/day. The amount of growth between metamorphosis and the end of the growing season (usually mid-September), and added to 16mm (the size at metamorphosis), predicted a size for toads at the end of their first year that almost exactly matched the average size of the first year cohort suggested by the size-frequency distributions. Applying the same average growth rate to suspected second and third year toads overestimated their average size at the end of the growing season. Under scanning electron and light microscopy, six individuals (SVL=38-65 mm) had one zone of spongy growth in sectioned toe bones and no lines of arrested growth (LAG); seven individuals (SVL=63-82 mm) had two zones of spongy growth and one LAG; and three individuals (SVL=81-85 mm) had three zones of spongy growth and two LAGs. These results strongly supported size-frequency and growth rate predictions; apparently only three generations of *B. microscaphus* comprise the population at Lytle Ranch.

This population is probably exceptional with regard to population size, although reports by Park naturalists (M. Hunnicutt, pers. comm.) indicated that large populations also occur along streams within Zion National Park. Certainly the Lytle population is many times larger than any population above or below the study area, and individuals are far more numerous than in populations of arroyo toads, *B. microscaphus californicus*, reported by Sweet (1991, 1993). Perhaps irrigated fields adjacent to the sandy stream zone inflate the area available for foraging; migration of toadlets and juveniles to these areas has been observed.

We cannot yet account for the skewed sex ratio. Breeding males are considerably smaller than clasped females, suggesting that males may be in their second year, whereas females may be in their third year. Calling males were heard in February 1997, but a sudden cold snap truncated the early breeding choruses. In March, many carcasses, some identifiable as males, were found macerated in the same areas where egg masses were subsequently observed. That males continue to call after females have ceased to be receptive suggests an energy loss for, as well as potential predation on, those individuals.

Clearly, the number of adult toads estimated to be at Lytle Ranch is a fraction of the biotic potential of the breeding population. Although we cannot account for all of the apparent mortality, we can say that eggs are damaged directly by freezing temperatures, predators such as crayfish, and pools that dry prematurely. We have also observed dead or dying tadpoles in drying pools, and predation on tadpoles by killdeer (first reported for arroyo toads by Sweet, 1991). However, all tadpoles metamorphose just before the stream begins to dry up in early to mid-June. Consequently, future studies on mortality need to concentrate on factors affecting toadlets and adults.

Are Short-Lived Species More Prone to Extinction?

Corn (1994), paraphrasing from Olson (1992), stated, "Many species [of amphibians] are long-lived and occasional mass mortality of embryos or tadpoles can be tolerated." Although Corn followed this statement with a discussion on flash floods causing catastrophic mortality of adults, the implication is that many species have been selected to be long-lived to withstand the effects of drought. We believe this is a common misconception, partly because there is so little evidence for the age structure of many populations. In fact, *B. microscaphus* belongs to a clade of species within the genus *Bufo*, some species of which



seem to be very short-lived, among them *B. cognatus* (Bragg and Weese, 1950), *B. americanus* (Kalb and Zug, 1990), *B. woodhousii* (Clark, 1977) and *B. baxteri* and *B. houstonensis* (A. Graybeal, pers. comm.).

A natural question is why some species living in drought-prone environments have continued to have short lifespans. *Bufo microscaphus* is a relictual, refugial species, confined to riparian zones from a time, several thousand years ago, when a wetter southwest became more arid (Maxson et al., 1981; Price and Sullivan, 1988). If these refugial streams never dried up during the peak times of breeding, there would be no selection for whatever variation in longevity might have existed in those populations. Consequently, the short lifespan of *B. microscaphus* may be simply a phylogenetic artifact. We believe that it is important to consider the phylogeny of amphibian species so that their ecology can be superimposed on those hypothesized relationships. Patterns detected from these comparisons may reveal important insights about a population's ability to survive various environmental conditions (or changes).

Management Considerations

Is it probable that other western species of frogs and toads, known to be declining in numbers, may be short-lived? Is there a relationship between short-lived species and the whole problem of declining amphibians? Support for these notions for a number of native species of the genus *Rana* are accumulating, and some herpetologists question whether populations of some desert-adapted species, like *Spea intermontana*, are long-lived (B.K. Sullivan, pers. comm.). The classic view of desert amphibians resisting drought by aestivation, long generation times, and sporadic, explosive breeding, might be replaced by a metapopulation model, where local extinction and recolonization are functions of prolonged droughts and periodic flooding, respectively.

One study on one population does not conclusively answer these questions. However, we believe identifying one population of a restricted, desert species having only three generations does warrant asking those questions and provides a direction for future studies that may yield important results for conservation and management of amphibian species in this region.

Amphibian species with three generations must reproduce for at least two of every three breeding seasons. Climatic changes that prevent breeding through droughts, flash-flooding or other agents, over geologic time, select for changes in life histories. Under these conditions, populations either adapt or die. Local extinction may or may not be reversed by recolonization. Studies have shown that although natural hybridization with *B. woodhousii* occurs at the mouth of every stream in southern Utah that supports *B. microscaphus*, the hybrid zones are narrowly defined and have remained stable for the last 40 years (Blair, 1955; Sullivan, 1995). These are natural processes that have operated throughout the history of life. Some of them (e.g., species selection) lead to greater diversity by further isolating already divergent and semi-isolated populations that subsequently survive to become new species (Stanley, 1979). It is because of this that reintroduction of individuals into areas where they are believed to have gone extinct requires a thorough understanding of the effects such introductions may have on evolutionary processes.

Our main concerns are human-induced changes to the environment that prematurely and directionally affect the status of amphibian populations. For example, regional development that requires water from surface or underground sources may, through damming streams or lowering ground-water levels, adversely affect the survival of short-lived amphibians. During the 1997 breeding season, water was diverted from an overflowing catchment and 15 percent of the egg masses in the study area dried up within a week. We, and others (e.g., K. Harper, pers. comm.), have observed planted stands of cottonwood trees



that lowered water tables by transpiration, resulting in a diurnal cessation of downstream flow in hot summer months. Sweet (1991, 1993) reported high mortality in *B. m. californicus*, from off-road vehicles and people trampling egg masses and newly hatched tadpoles near campgrounds in Los Padres National Forest.

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The Flora of the Colorado Plateau: What Do We Know?

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ABSTRACT

■ Of the five major floristic divisions in the State of Utah, none is richer in plant diversity than the Colorado Plateau division. The area set aside in 1996 and approved in 1997 as the Grand Staircase-Escalante National Monument is one part of this division, occupying 1.7 million acres. This area of precipitous canyons and high plateaus may harbor more than 1,100 species of vascular plants, or approximately 50 percent of the flora found in the Colorado Plateau and 30 percent of the flora of Utah. We know that as many as 40 species of rare and sensitive species are in the area. Statistics are drawn from existing digitized databases of plant distributions within Utah. A coordinated system of electronic databases is needed to track and analyze new information arising from ongoing botanical inventories. Geographic information systems will help organize data and link statewide biodiversity studies to nationwide data systems.

As those of us gathered for this symposium

know, few areas in the United States have attracted as much attention in recent years as the Colorado Plateau. The visual beauty of the area has inspired poets, captured the imagination of filmmakers, and is now attracting tourists in numbers that far exceed the carrying capacity of local communities. As a place of relatively unspoiled landscapes where layered rock holds a story of much of the earth's history, the Colorado Plateau offers an unusual opportunity for scientists. This area's potential to interweave studies of physical and natural science in order to understand the effects of climate and geology on the development of a flora and fauna may be unequalled in any other part of the world. This area of Utah is a natural biological laboratory ideally situated for a National Monument designated science-friendly by Presidential proclamation.

Thirty years ago, botanists would have had little information to contribute to a symposium on the Grand Staircase-Escalante National Monument in southern Utah. Today, thanks in large part to the establishment of the Endangered Species Act (Public Law 93-205), we know a great deal about the distribution of

species within the Monument's 1.7-million-acre area. We also know a great deal about the flora of other parts of the Colorado Plateau. The Federal regulations requiring environmental assessments on public lands allowed botanists to explore remote canyons in search of species considered rare, and with restricted distributions. In the red rock country of "layer-cake geology" where there is an obvious relationship between species distributions and geological substrate, botanists soon learned to use geological strata to predict particular plant assemblages. Field botanists learned intuitively to refine their exploration strategies in accord with what was known about the physical environment. The result has been a wealth of collections and discoveries of species new to science.

So, where are we to start with floristic studies in relatively unexplored and remote regions? The intent of this brief presentation is to: 1) summarize what is known about the composition of the flora, 2) discuss the utility of a model that will predict the probability that a species will occur in certain areas, and 3) present a plea for the development of statewide



information systems that will facilitate the extraction and exchange of data among scientists and public agencies.

What Do We Know?

Sources of Information

Collections made by scientists over the past 100 years, and particularly during the 1970's and 1980's, provide most of the information we have about species diversity in the Colorado Plateaus. Original records are found in major herbaria in the state.

Utah is the only state in the nation with an electronic database containing the geographic locations of most of the plant collections ever made in the area. The digital atlas of Utah (Ramsey et al., 1998) is available on the Internet (<http://www.nr.usu.edu>). The system documents approximately 400,000 plant specimens (vouchers) housed in various natural history collections in the state. In 1980, three botanists started the work of critically examining these specimens (individually verifying the identifications) and plotting their distributions on a base relief map. The work continued over a period of 7 years, and was eventually published as the *Atlas of the Vascular Plants of Utah* (Albee et al., 1988). Most of what we know today about species distributions in Utah is summarized in this work, and *A Flora of Utah* (Welsh et al., 1993) provides authoritative taxonomic keys and comprehensive descriptions of the flora. Electronic conversion of the biodiversity data contained in the atlas was completed in 1995; the digital version is maintained within the College of Natural Resources Internet site at Utah State University (<http://www.nr.usu.edu/Geography-Department/utgeog/utvatlas/ut-vascatlas.html>). The digital format is significant and highly useful in that it gives us the capacity to analyze patterns of species diversity in relation to regional ecosystems, landforms, and elevation. Species richness patterns for plants, for example, are shown by displaying species occurrence

records within a standard grid system for the state (Figure 1).

Natural history collections in the form of voucher specimens provide physical documentation for botanical studies. Universities house most of the plant collections in Utah, with major herbaria located at Brigham Young University, University of Utah (the Garrett Herbarium), and Utah State University (the Intermountain Herbarium). Smaller, but nonetheless very significant, collections are found at Weber University, Southern Utah State University, National Parks and Monuments, and District Offices of the Forest Service and Bureau of Land Management. Records that are especially relevant to studies of the flora of the Grand Staircase-Escalante National Monument are at Bryce Canyon National Park, Zion National Park, Capitol Reef National Park, and offices of the Bureau of Land Management in Cedar City and St. George. All specimens housed in the state and collected before 1988 are documented in the digital atlas, thus providing a source of

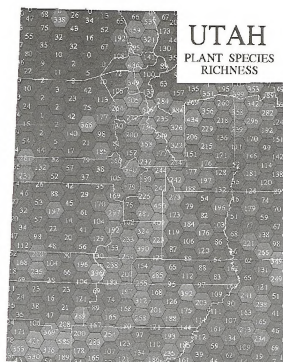


Figure 1. Species richness map for Utah, based on the *Atlas of the Vascular Plants of Utah* (Albee et al., 1988), the composite index made possible by the digitized format of the atlas (Ramsey et al., 1998)



information that far exceeds the resources of any one collection.

Detailed information about rare species is contained in a number of different publications. Of particular note are a summary of rare plants by Welsh and Chatterley (1985) and a field guide, published as a multiagency cooperative project, that provides photographs, descriptions, and distribution maps (Atwood et al., 1991). In addition, a massive review of rare plants in Utah provides current information about Federal, State, and global rankings (Stone, 1997).

Summary Statistics

The Colorado Plateaus have more plant diversity than any other floristic region in Utah, accounting for approximately 85 percent of the total diversity of vascular plants (Table 1). The region also harbors approximately 50 percent of the 250 species of plants endemic to Utah (Shultz, 1993). More than 2,500 species of indigenous plants occur in the Plateaus, a calculation drawn from 30,150 sample points contained in the digital version of the Utah atlas of plants (Ramsey et al., 1998). A checklist generated from the digitized atlas shows 1,369 species of vascular plants reported for Kane and Garfield Counties, including the 822 species reported for the Kaiparowits Plateau

Table 1. Distribution of species of vascular plants and collection activity shown by geographic region in Utah. The data are compiled from the *Atlas of Vascular Plants of Utah* (Albee et al., 1988), a work which documents 73,219 different collection localities (most with multiple records of species) for 2,822 species known from Utah. The maps record approximately 400,000 voucher collections in the State and account for all but the rarest populations (385 species have general localities listed in an Appendix). Analyses are from the digital format of the atlas (Ramsey et al., 1998).

Ecoregion	Percent of State (Land Mass)	Percent of Samples (n = 73,219)	Percent of Species (n = 2,822)
Colorado Plateau	41.05	42.30	84.17
Great Basin	39.91	21.21	67.06
Wasatch/ Uinta Mountains	18.11	35.56	75.96
Mohave Desert	0.22	0.53	14.40
Wyoming Plateau	1.71	1.75	26.05

(Welsh et al., 1978). Examining the county lists for species that may occur in habitats included within the Grand Staircase-Escalante area, I find more than 200 plant species that could be added to the checklist for the new Monument. Vascular plant diversity for the Monument could thus approach 1,100 species, or approximately one-third of all the species known in Utah. Thirty-nine species of rare plants occurring in Kane and Garfield Counties have been proposed for Federal protection as threatened, endangered, or sensitive (Welsh and Chatterley, 1985). Because many areas of the Monument have never been explored, new habitats and undescribed species undoubtedly will be discovered.

Inasmuch as the potential diversity for the new Monument represents more than 50 percent of the diversity for all of the Colorado Plateaus and approximately 40 percent of the rare species, we know that the Grand-Staircase Escalante National Monument is an area of particularly high species diversity and endemism.

Close examination of the species richness map for Utah (Figure 1) shows polygons of low diversity interspersed among polygons of high diversity. The explanation comes from the history of exploration of the area rather than any obvious difference in habitats. Areas of high diversity are documented by relatively high levels of collecting activity (i.e., the study of the Kaiparowits Plateau during the 1970's), while contiguous areas of low diversity can be explained by data gaps resulting from the absence of intensive collecting activity.

The reason for large data gaps in species distributions will be apparent to anyone visiting the Monument. Remote areas, steep slopes, and virtually inaccessible regions may keep many areas from ever being examined. We can at least identify gaps in our knowledge by combining all known collecting points recorded in the digital atlas, from which a transformed view is provided in Figure 1. Even so, many areas will remain beyond the reach of practical field studies. What we need, then, is to build information systems that will help us map



what we know about the flora and develop predictive models from data gathered in the field. We can generate maps showing the probability that a rare species might occur in an area that is either unexplored or affected by past disturbances.

Developing Shared Information Systems

Geographic Databases

Integrating spatially explicit information about plant distributions into a geographic information system (GIS) provides a basis for statistical analysis of floristic patterns at local, state, and national scales (Shultz et al., 1997). In the past 5 years, Utah State University's inventories of military lands in Utah have served as models for the development of coordinated databases using geographic information system (GIS) technology (Shultz et al., 1994). The databases have been designed for integration with geographic information systems designed for use with personal computers (ArcView) and are distributed on computer disks (CD-ROM) to land managers and researchers working in the area. In addition, Internet web sites are maintained for the projects (<http://www.nr.usu.edu/~hafb/hafb.html>; <http://www.nr.usu.edu/ned/nedhome.html>). These systems are used in environmental planning, management, and basic research.

Floristic Databases

In addition to geographic distributions, floristic data provides descriptive information about species in the form of hierarchical taxonomies, identifying features, and ecological information. If constructed for maximum utility, floristic databases will be searchable in many forms. Ideally, a user would be able to search a database by looking for common names, scientific names, growth forms (i.e., tree vs. shrub), status (i.e., native vs. exotic; rare vs. widespread), and generate a list of species for any category. The databases we have constructed for Great Basin ecosystems at the Floristics Laboratory

at Utah State University (Department of Forest Resources) can be searched by any of these fields, and more. In addition, a list of species can be generated for any geographic area. In order to provide information in a format that can be incorporated into geographic information systems, the format of the floristic databases should be designed to conform to standard herbarium databases (Shultz and Hysell, 1996). Examples of working, coordinated systems are provided by reports of collaborative efforts between the College of Natural Resources at Utah State University and the Utah Army National Guard, the Bureau of Land Management, U.S. Air Force, and Utah Division of Wildlife Resources.

In building a georeferenced database for rare species, a query-oriented system can be developed that provides information to the user at several levels. We referenced both published records and herbarium collections, developing a database of specific localities for the sensitive species, as well as links to the published literature. Specific data points are nested within a spatial hierarchy of hexagons or grids, allowing the user to point to a map, click on an area of interest, and get a list of the ecological and taxonomic literature relevant to the area, as well as generalized collection locality information. For rare plant populations, locations are displayed at the resolution of a township rather than a point. Limiting the display of information to this scale (1:6,150,000) protects sensitive locality information.

Predictive Models

Using geographic information systems and floristic databases, we can begin to close the gaps in information for remote and inaccessible areas by developing predictive models that estimate the likelihood that a species will occur in any given area. In concentrating our studies on species of limited distribution, we have expanded the data system to include site-specific data about sensitive populations. This system forms the basis of a project to predict populations of threatened, endangered, or sensitive species using a hierarchical tree classifier model in systems developed by David Roberts



of Utah State University. Aitken (1998) has worked to define critical habitat for four rare species in the Great Basin. After two seasons of field work, she has demonstrated the utility of the model for mapping potential habitat in unexplored areas and has shown the correlation of different environmental and biological associations with species distributions. The system generates maps estimating different levels of probability that a species occurs in a particular area.

The study of rare plant habitats in the Great Basin is based on a set of georeferenced sample plots established for discrete populations of plants (Sharik et al., 1997). Point-specific data is recorded within the geographic information system and referenced in a system analyzed for environmental variables. Presence/absence data for associated species are gathered at each of the plots and habitats are described in terms of physical properties. In the field, we use global positioning systems to take specific location readings, and other instrumentation to take independent measures of elevation, slope, and aspect. Soil samples and voucher specimens are collected as appropriate. In analysis, the crucial environmental attributes are arrayed in a set of ranges for continuous variables or classes for categorical variables. Each environmental variable becomes a separate layer in the geographic information system. In the computer model used to develop maps of predicted habitats of rare species, physical environmental layers are intersected to determine the set of all possible environmental combinations. A hierarchical tree classifier is then used to rank the relative importance of each of the variables in predicting the distribution of a particular species. Two independent tests are run: one based on data taken from the field, and one from data that is resident in the geographic information system.

Our underlying assumption is that at a landscape level, patterns of distribution are controlled by localized edaphic factors such as elevation, slope, aspect, moisture gradients, and geology. The results of our analyses for distributions of rare species demonstrate the degree to which different independent variables can predict the

distribution of a particular species. By comparing the analyses based on field-collected data to analyses drawn from information resident in existing geographic information systems, we can assess the relative utility of intensive field sampling efforts. At a practical level, we have used the maps generated by the predictive model to direct our field work in previously unexplored areas and have been successful in predicting new (i.e., previously undocumented) populations of rare species. Using independent environmental variables to develop models predicting critical habitat for rare species, we can develop hypotheses concerning the factors influencing species distributions through time. And, by mapping distributions of species, we are documenting patterns of biodiversity in the context of landscapes.

Future Research

In an area as vast as the new Grand-Staircase Escalante National Monument, efficient methodologies for collecting and distributing information about the biota are clearly needed. In developing strategies to study this largely unexplored ecosystem, this symposium takes the critical first steps to identify gaps in our knowledge and prioritize directions for new research. If we develop information about biodiversity in a way that will be useful in new management systems as well as in research programs, scientists working in this area will have an advantage unknown in any other part of the country.

Sustaining the effort to record, document, and examine critically all new collections in Utah in a coordinated information system is a responsibility that, to date, no individual or institution has been willing to accept. Nonetheless, timing is critical if we are to keep the gap in current information between published works and new inventories from widening. Developing systems that incorporate data from current inventories is essential to maintaining the utility of our data on biodiversity for the state. We are presented with an unusual opportunity in Utah: to develop a state-level



biodiversity database by merely taking advantage of the information already integrated into geographic information systems and developing guidelines for the continued growth of the system.

By bringing scientists from various disciplines together in this symposium, we have an unusual opportunity to develop goals for interdisciplinary research. Collaborative multiagency efforts can help to increase our knowledge about biodiversity. There has never been a better time to go beyond simple cataloguing efforts and begin to ask questions about the relationships of the biophysical environment and patterns of vegetation. In addition to simple descriptions of species distributions, we should use the tools we have available to quantify and analyze patterns of biodiversity. Before geographic information systems were available, we could employ labor-intensive methods to analyze the similarities among floras, thereby defining physiographic areas at regional (McLaughlin, 1986) and local scales (Shultz et al., 1987). Now, with the organizational and analytical capacity of geographic information systems, we can develop practical managerial systems and extend our analytical capacity. Utilizing the information at hand, we can analyze the effects of climate and geology on the development of the flora and fauna of Utah, learn to predict the effects of change, and enlarge our understanding of this unique and richly diverse ecosystem. With minimal effort, spatially explicit information systems can facilitate conservation efforts and help land managers mitigate the effects of future impacts on the flora and fauna. The benefit of these data systems is evident not only in a study of ecological processes, but also in public education and applied management systems.

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Metapopulations of Bighorn Sheep in 15 National Park Units in the Intermountain Region: The Restoration and Conservation Biology of a Severely Fragmented Species

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ABSTRACT

■ Bighorn sheep (*Ovis canadensis*) were historically a highly successful species and were abundant in all of the mountains, foothills, and prairie badlands of the western United States. However, due to catastrophic declines in the late 1800's and early 1900's, most extant populations now exist as small, isolated groups occurring in a highly fragmented distribution. These small populations are more prone to extirpation than larger ones due to stochastic events such as seasonal weather changes or population fluctuations.

Bighorn sheep from 3 different subspecies were eliminated from 14 of 18 National Park units in the 6-state Intermountain Region of the western United States. In 1990, when this restoration effort was initiated only 4 of 22 discrete Park populations/metapopulations (18 percent) were considered large enough to be secure for long-term management goals, 5 other populations (23 percent) were rated secure for short-term goals of a few decades only, 3 populations (14 percent) were rated moderately secure for short-term goals, while the remaining 10 populations (45 percent) were either extirpated ($n=2$), remnant ($n=5$) or were highly vulnerable to extirpation ($n=3$). Restoration efforts were highly successful in one unit, but success was only low to moderate in the remaining units. One population of bighorn sheep is Federally listed as endangered. The species meets all of the criteria of a species at risk, requiring immediate attention to keep some other populations from being listed. Since a few populations are large and healthy enough to provide source stock, and since it is relatively uncomplicated to capture and move bighorn sheep, aggressive restoration activities were recommended in 1990 for 15 of the National Park units in the Intermountain Region.

This report details the efforts of a 6-year initiative to restore bighorn sheep to all occupiable historic habitat within the Parks of the Intermountain Region. The purpose of the first phase of the initiative, 1991-93, was to conduct research



and population surveys and to plan the restoration efforts. The purpose of the second phase of the initiative, 1994-96, was to conduct geographic information system-based habitat and biological assessments of prospective restoration sites, to write restoration plans, and to restore and monitor the released bighorns.

A 7-point program was recommended for each Park during the assessment and restoration phases, including: 1) survey existing populations, 2) conduct GIS-based habitat assessment, 3) convene scientific panels, 4) convene interagency meetings to discuss and plan and restoration, 5) draft metapopulation interagency restoration plan, 6) conduct translocation(s) or other management, and 7) monitor the management activities. This 7-point assessment and restoration process was applied to the remaining 14 National Park units from 1994 to 1996.



The Grand Staircase-Escalante National Monument History of Plant Collecting and Collections, 1872-Present

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As in any discipline, knowledge of the plants residing within the Grand Staircase-Escalante National Monument (GSENM) has grown through time. The database has developed from a point in time only somewhat more than a century ago, when such data was completely lacking, to the present, when considerable information is available. Literally thousands of plant specimens are now available in herbaria, which will form the database for construction of a definitive flora of the GSENM. There is no need to start from scratch because of the efforts through many decades. Work now in progress will focus on those portions of the Monument that have received little or no work in the past.

ABSTRACT

■ Summarized is the plant taxonomic baseline information on the Kaiparowits and Kane County portions of the Grand Staircase-Escalante National Monument and environs. Focus of the report is the vascular flora within the National Monument.

Historical Overview

One way of charting the accumulation of knowledge of plants for a given area is to observe the progression of new taxa published therefrom.

Apparently the first attempt at cataloging of plants from the near vicinity of the Monument, if not within that entity as presently understood, occurred in the 1870's. Residing at Kanab in 1872 (Gregory 1939), Ellen Powell Thompson (sister of John Wesley Powell), wife of Almon Harris Thompson (member of the Powell survey), collected the type materials of some 15 new taxa; most of them were published by Watson (1873), but some by Gray (1878). The widespread *Astragalus thompsonae* S. Watson and the edaphically restricted *A. ampullarius* S. Wats. are among her finds. Other species that are attributed to her collections, though some were undoubtedly contributed by her husband, are *Androstaphyllum breviflorum* S. Watson, the beautiful sego lilies *Calochortus aureus* S. Watson and *C. flexuosus* S. Watson, *Erigeron stenophyllus* var. *tetrapleuris* A. Gray, *Eriogonum thompsonae* S. Watson, *Oenothera multijuga* S. Watson, *Oxybaphus glaber* S.



Watson, *Parosella thompsonae* S. Watson, *Penstemon pumilus* var. *thompsoniae* A. Gray, *Petalostemon flavescens* S. Watson, *Peteria thompsonae* S. Watson, *Psathyrotes pilifera* A. Gray, *Riddellia tagetina* var. *sparsiflora* A. Gray, and *Whipplea utahensis* S. Watson (see Welsh et al., 1993 for modern equivalents). All of these, except for the *Parosella*, are currently known from within the GSENM. They were the first of a rather large series of plant taxa to be described from within or immediately adjacent to the Monument.

Places of publication of types up until 1981 are included in a paper on Utah plant types (Welsh, 1982).

Francis Marion Bishop, who was also with the Powell survey, collected certain specimens, but failed to record exact localities. Probably most of his collections are from Kane County. Among them are *Astragalus episcopus* S. Watson (named after Bishop), *Astragalus sesquiflorus* S. Watson, *Eritrichium holopterum* S. Watson, and *Riddellia tagetina* S. Watson.

Perhaps the most colorful of the collectors of type specimens from Kane County was Alfred L. Siler, who lived alternately at Kanab and at a place called simply "ranch," near the head of the Sevier River. Included among his 1873 and 1875 collections are *Clematis pseudotragene* ssp. *wenderothoides* Kuntze, *Eriogonum triste* S. Watson, *Lupinus sileri* S. Watson, *Penstemon linarioides* var. *sileri* A. Gray, *Shepherdia rotundifolia* C.C. Parry (valley of the Virgin).

Western Kane County was traversed by the remarkable pioneer Utah botanist Marcus E. Jones in his historic 1894 and earlier 1890 collecting trips. Among the plants named from his collections are *Aster glaucodes* ssp. *pulcher* S.F. Blake, *Astragalus haydenianus* var. *major* M.E. Jones (from Johnson), *Astragalus silerianus* var. *caraicus* M.E. Jones, *Caulanthus crassicaulis* var. *glaber* M.E. Jones, *Ceanothus fendleri* var. *viridis* M.E. Jones, *Cnicus nidulus* M.E. Jones, *Frasera utahensis* M.E. Jones, *Krynitzkia leucophaea* var. *alata* M.E. Jones, *Linum kingii* var. *pinetorum* M.E. Jones, *Muhlenbergia curtifolia* Scribner, and *Schmaltzia affinis* Greene.

Alfred Wetherill visited Kane County in 1897 and collected the type of *Ptelea neglecta* Greene. The hop-tree has eluded most botanists since that time; it is relatively common to the south in Arizona.

A U.S. Forest Service worker named Malmsten collected the type of *Senecio malmstenii* S.F. Blake from Little Podunk Creek, Kane County, in 1916.

Miss Alice Eastwood, accompanied by John Thomas Howell, collected the type of *Townsendia minima* Eastwood in Bryce Canyon in 1933.

The distinctive *Yucca kanabensis* McKelvey was taken by her in 1934, between Mount Carmel and Kanab.

Kane County was visited by ardent collector Bassett Maguire in 1935, when he took the type of *Penstemon palmeri* ssp. *eglandulosus* Keck, some 2.5 miles north of Kanab. That same year, the amazing Walter P. Cottam collected the type of *Polygonum utahense* Brenckle and Cottam from 6 miles north of Escalante.

Clover (1938) visited Hell's Backbone north of Escalante in 1937 and collected the type of *Coryphantha marstonii* Clover (unfortunately the type was not saved). That is also the type locality of *Lepidium montanum* var. *neeseae* Welsh, taken by Neese in 1977.

The type specimen of the endemic *Astragalus malacoides* Barneby (1964) was taken from atop the Straight Cliffs above Fifty-Mile Cabin on May 9, 1939 by Bertrand F. Harrison. That same year, a person named Tompkins collected the type of *Phacelia pulchella* var. *sabulorum* J.T. Howell from the Kaiparowits Plateau.

The region was again visited by Eastwood and Howell in 1941. At Kanab, on May 11, they collected the tall, pale-flowered *Thelypodopsis ambigua* (S. Watson) Al-Shehbaz. Their collection was later designated as the type of the var. *erecta* Rollins (1982). They were followed the next year by Rupert C. Barneby and



Dwight Ripley, who took the type of *Psoralea epipsila* Barneby some 17 miles east of Kanab. Both taxa are edaphic endemics, the former growing mainly on the Chinle Formation, and the latter on the Moenkopi Formation.

The beautiful *Lathyrus zionis* C.L. Hitchcock was described from a plant taken by its author in 1949 some 10 miles east of Zion National Park, Kane County.

The edaphically restricted *Machaeranthera glabriuscula* var. *confertiflora* Cronquist was taken by its author in 1961, some 11 miles northeast of Henrieville.

Two unusual endemic species were described from Cottonwood Canyon by Barneby in 1966; *Euphorbia nephradenia* Barneby and *Viguiera soliceps* Barneby. Both are edaphically restricted species, peculiar to saline, seleniferous substrates of the Tropic Shale Formation. Also named that year was *Lesquerella hitchcockii* ssp. *tumulosa* Barneby (from southeast of Cannonville).

The type of *Phacelia constancei* was collected south of Kanab in adjacent Arizona by N.D. Atwood in May 1968.

Several new taxa were named based on specimens taken on the Navajo-Kaiparowits Project by personnel from Brigham Young University, including: *Astragalus lentiginosus* var. *wahweapensis* Welsh (in 1974, from Four Mile Bench), *Camissonia atwoodii* Cronquist (from Smoky Mt., Atwood in 1973), *Cymopterus higginsii* (in 1975, circa 17 miles east of Glen Canyon City), *Iris pariensis* Welsh (in 1976, by Vane Campbell on East Clark Bench), *Lepidium montanum* var. *stellae* Welsh & Reveal (southeast of Cannonville), *Penstemon atwoodii* Welsh (in 1975, south-southeast of Canaan Peak), *Psoralea pariensis* Welsh & Atwood (in 1975, from Bryce Canyon), *Xylorkhiza cronquistii* Welsh & Atwood (in 1975, from Horse Mountain). The bibliographic citation for some of these is Welsh (1986).

The remarkable psammophyte, *Asclepias welshii* N. & P. Holmgren, was collected by the

Holmgrens from the Coral Pink Sand Dunes in 1978 (Holmgren and Holmgren, 1979).

The type of the remarkable *Penstemon ammophilus* N. Holmgren & L. Shultz (1982) was collected in 1981 on Canaan Mountain, Washington County. It was found that same year by Welsh below the White Cliffs in a tributary of Johnson Canyon, Kane County.

In 1983, N.D. Atwood collected the type of *Phacelia cronquistiana* Welsh at the head of Johnson Canyon. Higgins, Welsh, and Thorne collected the type of *Cryptantha cinerea* var. *arenicola* Higgins & Welsh in Johnson Canyon in 1984. Welsh and Thorne took the type of *Phacelia pulchella* var. *atwoodii* Welsh, in 1992 some 10 miles east of Johnson Canyon (Welsh, 1993).

Corispermum welshii Mosyakin (1995) is based on a type collection by Welsh and Thorne in 1992 from the Coral Pink Dunes.

A great deal of work peripheral to the GSENM was done in the period 1935 to 1957, primarily associated with Glen Canyon and Navajo Mountain. Important works both within and adjacent to GSENM include Benson (1935), Crampton (1959), Gregory (1939, 1945), Gregory and Moore (1931), Hayward et al. (1958), Miller (1959), Presnall (1934), Tanner (1940), and Woodbury et al. (1959).

Perhaps the most pertinent historical biological investigations to fall within or adjacent to the GSENM were those by members of the Zoology Department at Brigham Young University. In July 1927, they visited Lee's Ferry and Bryce Canyon, and in 1936, a party of four biologists spent about 80 staff-days in the Escalante River drainage (Hayward et al., 1958). Vasco M. Tanner, and C. Lynn Hayward investigated portions of the Paria Valley in 1937, and D. Elden Beck explored along the Escalante River during 1938 and 1939. A portion of this work was summarized by Tanner (1940). During May and June of 1940, Beck worked in the vicinity of Willow Spring Tank on the Escalante River. Additional work was



done by various workers from Brigham Young University in 1946, 1952, 1953, 1955, and 1958 (Hayward et al., 1958).

The Navajo-Kaiparowits Project directed by Brigham Young University personnel yielded huge amounts of biological information. Two major papers resulted from that project, including one by Welsh et al. (1978) dealing with the Kaiparowits flora. That paper recognizes some 851 taxa (822 species and 29 infra-specific taxa) in 358 genera and 80 families of vascular plants. The treatment includes areas outside of the GSENM, however. It includes a portion of the Glen Canyon Recreation Area as well. Among the plants recognized as unique, either because of rarity or other considerations, are the following (not including some species now regarded as common, as synonyms, or as being outside the GSENM): *Astragalus emoryanus* (at the edge of is range in Kane County), *Astragalus hallii* var. *fallax* (disjunct at the foot of the Pink Cliffs, Grand Staircase), *Astragalus kentrophyta* var. *coloradoensis* (a Glen Canyon endemic), *Astragalus malacoides* (a Kaiparowits vicinity endemic), *Camissonia atwoodii* (a Kaiparowits-Glen Canyon endemic), *Euphorbia nephradenia* (a narrowly restricted endemic), *Gilia latifolia* var. *imperialis* (a Glen Canyon endemic), *Lesquerella rubicundula* (Red Canyon-Bryce endemic), *Lesquerella tumulosa* (a Windsor Formation endemic), *Phacelia cephalotes* (an endemic of gypsiferous clay strata), *Phacelia mammillariensis* (a Kaiparowits-Glen Canyon endemic), *Phacelia constancei* (restricted to the Moenkopi Formation), *Pediomelum epiptilum* (an edaphic endemic), *Viguiera soliceps* (a Tropic Shale endemic), and *Xylorhiza confertiflora* (a Kaiparowits endemic).

The second paper, by Atwood et al. (1980), listed the terrestrial vertebrate fauna of the Kaiparowits Basin, cited vegetation communities studied, and addressed some of the early history of previous biological research done in the region. The treatment includes 8 amphibians, 32 reptiles, 186 birds, and 72 mammals. The two published papers from the Navajo-Kaiparowits Project, cited above, address only the flora and fauna, but additional data were

collected on soils, litter, vegetation, climate, trace elements, animal pathology, small mammal populations, and hanging gardens.

A report to the Bureau of Land Management by Welsh and Eliason (1995) on sensitive plant species and a listing of the flora of Kane County, Utah, consisted of a compilation of those species taken during the collecting seasons of 1992, 1993, and 1994, as well as information extracted from the 1978 paper by Welsh et al. Cited are 79 vascular plant families, 304 genera, and 652 species. The list was not presented as exhaustive, even for Kane County; many of the most commonly encountered species were not treated. Certainly there are at least some species in the GSENM. Additional species are known from within or immediately adjacent to the GSENM, especially in the Garfield County portion. Many of them are cited in the Kaiparowits flora (Welsh et al., 1978), and will be added to a GSENM floral listing.

A preliminary *Flora of Glen Canyon National Recreation Area* (Welsh, 1984) treats some 556 species of plants from that region, which is immediately adjacent to the GSENM. Many of the plant species are shared with the Monument, but some are not currently reported for it.

Welsh and Eliason (1995) cited 19 taxa on the BLM sensitive species list, including the following, which are Federally listed as threatened: *Asclepias welshii* N. & P. Holmgren, *Astragalus ampullarius* S. Watson, *Camissonia atwoodii* Cronquist, *Camissonia exilis* (Raven) Raven, *Cryptantha cinerea* var. *arenicola* Higgins & Welsh, *Cycladenia humilis* var. *jonesii* (Eastwood) Welsh & Atwood (found nearby in Mohave County, Arizona), *Cymopterus higginsii* Welsh, *Erigeron canaani* Welsh (known from immediately west of Kane County), *Erigeron sionis* Cronquist (known from immediately west of Kane County), *Heterotheca jonesii* (S.F. Blake) Welsh & Atwood, *Iris pariensis* Welsh, *Jamesia americana* var. *zionis* N. Holmgren (known from immediately west of Kane County), *Lepidium montanum* var. *stellae* Welsh & Reveal, the Federally listed endangered



Pediocactus sileri (Engelm.) L. Benson (not currently known from Kane County, but immediately adjacent in both Mohave County, Arizona and Washington County, Utah), *Pediomelum epipsilum* (Barneby) Welsh, *Pediomelum pariense* (Welsh & Atwood) Grimes, *Penstemon ammodendrus* N. Holmgren & L. Shultz, *Selaginella utahensis* Flowers (known from west of Kane County), and *Sphaeromeria ruthiae* Holmgren, Shultz, and Lowrey (also known from west of Kane County).

The Federally listed threatened *Spiranthes romanoffiana* var. *diluvialis* (Sheviak) Welsh occurs within the GSENM in the Deer Creek vicinity east of Boulder.

From information currently available, it seems probable that the GSENM supports almost 1,000 vascular plant taxa.

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Ecology of Mexican Spotted Owls (*Strix occidentalis lucida*) in the Canyonlands of Southern Utah and Potential Relationships to the GSENM

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Three subspecies
of spotted owl
are recognized in

North America: the

Mexican spotted owl

(*Strix occidentalis lucida*), the Northern spotted owl (*S. o. caurina*), and the California spotted owl (*S. o. occidentalis*) (Figure 1). A recent genetic study found one major allelic difference between the coastal subspecies (i.e., *caurina* and *occidentalis*) and the Mexican subspecies (Barrowclough and Gutiérrez, 1990).

ABSTRACT

■ We investigated aspects of Mexican spotted owl ecology in southern Utah's canyon country that are relevant to the owl's conservation and long-term management. The objectives of our study included: 1) describe adult home-range characteristics, 2) investigate natal dispersal behavior, and 3) model habitat association data to predict the most likely locations of spotted owls within southern Utah, including the Grand Staircase-Escalante National Monument. Mean home-range size for 15 adult owls was 1139 ha (Minimum Convex Polygon estimation, and 882 ha for the Adaptive Kernel estimate). Winter home-range size was greater than summer home ranges for 13 individuals. Activity centers were identified within all owl home ranges and were on average 279 ha in size. The owls were observed to roost in steep canyons with relatively high vegetation canopy cover and cool daytime temperatures. Juvenile owls dispersed from natal areas during September each year of the study. On average, the owlets traveled 25 km from the natal area to the point where radio transmitters failed, or the owls died. The juveniles may have crossed habitats judged unsuitable for spotted owls by previous investigators. A spotted owl predictive habitat model suggested that the Grand Staircase-Escalante National Monument possessed large tracts of potentially suitable breeding habitat for spotted owls. We believe that the predicted locations of breeding habitat should be a top priority for future inventory within the new Monument.

Regional genetic differences may also occur at the subpopulation level for *lucida*, with spotted owls in Utah showing distinct genetic variation from local populations to the south in Arizona and New Mexico (G. Barrowclough, pers. comm.).

Traditionally, spotted owls were associated with multilayered late seral forests with high

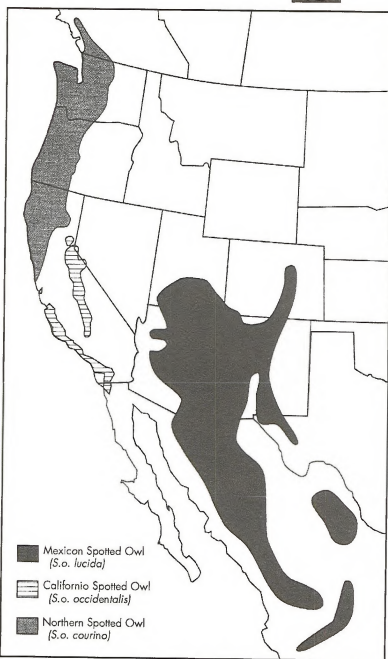


Figure 1. Distribution of spotted owls in the United States.

crown closure (Forsman et al., 1984; Ganey and Balda, 1989a, b, and 1994; Bias and Gutierrez, 1992; Blakesley et al., 1992; Hunter et al., 1995; Forsman and Giese, 1997; Grubb et al., 1997; LaHaye et al., 1997; Ripple et al., 1997). Because of perceived dependence on mature forest, spotted owls became a focal point for controversy over timber harvest in the western U.S. (Hunter, 1989; Thomas et al., 1990; Anderson and Mahato, 1995; Gutierrez et al., 1995). As a result, both the Northern and Mexican spotted owl are listed as "threatened species" under the

Endangered Species Act (Gutierrez et al., 1995). Timber management practices were identified as the primary threat to Mexican spotted owl breeding habitat in the southwest (Smith, 1990; Smith, 1991; Cully and Austin, 1993).

In contrast to the view that spotted owls require old growth habitat, the Mexican spotted owl in the Grand-Staircase-Escalante National Monument (GSENM) region of the Colorado Plateau inhabits relatively open habitat along the northwest edge of its range in Utah (Figure 1). Rinkevich (1991) and Willey (1995) confirmed breeding by Mexican spotted owls within isolated, and relatively xeric, canyon habitat scattered across southern Utah. In this region, the owl was associated with steep sandstone canyons that included the relatively open Great Basin desertscrub and Great Basin conifer woodland vegetation types (Brown, 1982). The open canyon habitat could be described as aberrant, considering the late seral forest requirements typically reported for the owl (Ganey and Balda, 1989a; Seamans and Gutierrez, 1995; Miller et al., 1997). Willey (1995) described the distribution of the owl in southern Utah and suggested that the owl was not dependent on mature forest vegetation.

The subpopulations in Utah represent potential sources important to the long-term persistence of the spotted owl; therefore, this region was designated as the Colorado Plateau Recovery Unit (USDI, 1995). Because Mexican spotted owls in this region are listed as threatened, information is needed to allow ecologically based conservation. Our research was designed to investigate Mexican spotted owls in habitat similar to that which occurs in



GSENM, focusing on the xeric canyon terrain of southern Utah. The objectives of our study included: 1) describe adult home-range characteristics, 2) investigate natal dispersal behavior, and 3) model habitat association data to predict the most likely locations of spotted owls within southern Utah, including the GSENM, using a geographic information system (GIS).

Study Areas

The field work was conducted in four primary study areas in southern Utah that form an arc around the GSENM: Zion National Park, Capitol Reef National Park, Canyonlands National Park, and the Manti LaSal National Forest. Similarly to habitats within the GSENM, all study areas were dominated by Great Basin conifer woodland and desertscrub (Brown, 1982), with small pockets of mixed conifer forests, dominated by Douglas fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*) and ponderosa pine (*Pinus ponderosa*) in cool side canyons and north-facing grottos. The uplands contained a mixture of pinyon-juniper woodlands interspersed by blackbrush (*Coleogyne ramosissima*) and curl-leaf mahogany (*Cercocarpus ledifolius*), with Indian ricegrass (*Stipa hymenoides*) in the understory. Mixed conifer forests were found along canyon bottoms. The canyon slopes contained mixed conifer forests on north-facing aspects, and ponderosa pine and pinyon-juniper woodlands on south-facing aspects. Mesa tops were dominated by pinyon-juniper woodlands and desertscrub vegetation. Elevations throughout the study areas ranged from 1109 to 3960 m. Total annual precipitation averaged 17 cm per year, and temperatures ranged seasonally from below 0 °C to 40 °C (U.S. Weather Bureau, Climate and Precipitation Summaries, Utah).

The Zion National Park study area was west of the GSENM, located 1 km north of Springdale, in southwestern Utah, and was characterized by a large canyon gorge bisected by steep sandstone canyons surrounded by high vertical cliffs and isolated mesas. The

Capitol Reef National Park study area, directly north of the GSENM, was located 25 km northeast of Torrey, in south-central Utah. Capitol Reef was characterized by entrenched sandstone canyons eroded into a 160 km north-south trending monocline extending from Glen Canyon National Recreation Area north to the Fishlake National Forest (Heil et al., 1995). The Canyonlands National Park study area was located 50 km northwest of Monticello, in southeastern Utah, and possessed numerous sandstone canyonlands and plateau highlands. Finally, the Manti LaSal National Forest study area, located 35 km east of Blanding, was characterized by entrenched sandstone canyonlands with large tracts of mixed conifer forest.

Methods

Mexican spotted owls were located in each study area by mimicking their calls with the human voice while traversing historic survey routes (Willey, 1995). Radiotelemetry was selected as the primary method of study because it was cost-effective and efficient, and provided accurate methods to locate owls and describe their seasonal habitat and movements (White and Garrott, 1990). Canyons occupied by spotted owls were approached during 0400-1000 hours or 1700-2000 hours to attempt to trap adult owls. Once an owl was found, Bal-Chatr traps were placed in prominent locations directly under the target owl (Forsman, 1983). Once an owl was trapped, it was quickly restrained, hooded, and prepared for tail-mounted radio attachment. Radio transmitters (Holohil Inc., Ontario, Canada), weighing 5.5-6.0 gm with an average signal life of 12±6 months, were attached to the two central tail feathers using quick-set epoxy and unwaxed dental floss. Radio signals were received using TR-1 and TR-2 receivers and handheld or airplane mounted H-antennas (Telonics Inc., Mesa, AZ). A Cessna 172 fixed-wing aircraft was used for all aerial tracking (Red-Tail Aviation, Moab). Locations were based on aerial fixes of roosting owls or visual observation of roosting owls. Nocturnal



locations were obtained by triangulation of compass bearings from ≥ 2 tracking stations placed above the canyon terrain so that the movements of owls could be followed with the reception equipment. Most nocturnal tracking was done on foot from cliff rims above the canyons using headlamps for illumination. All sightings were georeferenced and entered into a GIS using the ArcInfo software program (ESRI, 1996).

Results

Adult Seasonal Home-Range Characteristics

We obtained 2,312 estimated locations on 28 radio-tagged adult spotted owls over a 5-year period (1991-95). Eleven female and 17 male spotted owls were captured and radio-tagged. Five males and eight females molted their radios in 4 weeks. We constructed annual home-range estimates for 15 adult owls (Table 1). Home-range size was not correlated with sample size ($r_s = -0.311$, $n = 15$, $P > 0.05$). The

mean annual home-range size estimates were not significantly different between models (Table 1, $t = 1.36$, $df = 14$, $P = 0.195$, paired two-sample t -test). Mean size estimates were significantly different between summer (March 1 - August 31) and winter home ranges (September 1 - end of February) when we used the AK model for the contrast.

The pattern of spatial use by the adult owls indicated that the owls utilized activity centers within their home ranges. Activity centers were identified using AK75 percent kernels generated by Program TELEM (Kevin McKelvey, unpubl. software) that represented 75 percent of known locations for each owl. Mean size of AK75 percent contours was 279 ha and showed lower variability among the owls than the AK95 percent contours (Table 1). The AK75 percent kernels represented groups of owl locations that were centered around nests or roost sites. The clusters of owl locations may have been foraging areas (Call, 1990); however, a variety of nocturnal behaviors were possible, including rest, self-maintenance, calling, or monitoring presence of conspecifics or predators (Forsman et al., 1984).

Table 1. Home-range size estimates in hectares for 15 radiotagged Mexican spotted owls from Utah, 1991-95.

	Period ^a	Num ^b	MCP ^c	AK95 ^d	AK75 ^e
Twin male	2/92 - 11/94	306	1655	354	155
Spring male	5/91 - 7/93	184	733	1012	165
Hidden male	6/91 - 9/92	116	2102	1151	358
Echo male	5/91 - 7/94	99	271	120	39
Sams male	9/93 - 10/94	52	487	505	246
First male	1/91 - 8/94	87	670	618	78
Eleph male	1/91 - 7/94	102	1656	2478	317
Burro male	3/94 - 7/94	75	273	864	212
Pecovi male	9/92 - 10/93	52	1165	1169	343
Oldlex male	7/91 - 7/92	130	382	174	69
Newtex male	5/94 - 8/95	474	1579	341	180
Dark male	9/92 - 6/95	151	1638	852	297
Burro female	5/94 - 10/95	93	1025	1910	576
Hamm female	6/91 - 9/96	50	1528	819	819
Dark female	9/92 - 6/95	152	1924	879	334
Mean			1139	882	279
Standard Deviation			609	612	197

^a Tracking period by month and year.

^b Total number of estimated telemetry locations.

^c 100 percent Minimum Convex Polygon estimate.

^d 95 percent Adaptive Kernel estimate.

^e 75 percent Adaptive Kernel estimate.

We found that the distribution of owl home ranges appeared to coincide with the distribution of steep rocky canyon terrain. Within the rocky landscape, we observed an association between spotted owls and forest or riparian deciduous woodland vegetation. The owls were observed to roost in steep canyons with relatively high vegetation canopy cover and cool daytime temperatures. The roost sites possessed larger trees and had a greater number of caves and ledges than surrounding habitat. Pinyon-juniper woodland was the most common vegetation community present in adult home ranges (present at 42 percent of 780 habitat plots overall). Mixed forest vegetation, often including Douglas fir and white fir, ponderosa and pinyon pines, or Utah juniper was present at 31 percent of the random habitat



plots. Desertscrub vegetation covered 17 percent of the random plots, and Deciduous riparian vegetation, including box elder (*Acer negundo*), big-toothed maple (*Acer grandidentatum*), or Fremont cottonwood was identified at 10 percent of the plots.

Natal Dispersal Patterns

Thirty-two juveniles were captured and radio-tracked during 1992-95 (Table 2). In 1992 we radio-tagged two juveniles in Canyonlands, one juvenile in Texas Canyon near Elk Ridge, and four in Zion National Park. In 1993, six juveniles were radio-tagged in Zion and three near Elk Ridge. In 1994, seven juveniles were monitored in Capitol Reef, two in Zion, and one on Elk Ridge. In 1995 I radio-tagged five juveniles in Capitol Reef and two juveniles near Elk Ridge. The juveniles remained relatively close to their nest sites (range = 67-520 m) until dispersal. First year mortality was high for the juveniles, with only 3 of the 27 dispersing juveniles (11.1 percent) still alive after 1 year. Twenty-four owlets died or their signal was lost from the sample due to radio failure or an inability to relocate the owl after extensive searches. The three owlets that survived their first year settled within defined

home ranges and were still active until the radio signals were lost during summer and fall 1993. None of the three juveniles that survived 1 year were found with mates before their radios failed.

During dispersal, individual owls crossed a wide variety of landscapes and habitats. The owls moved up and down slopes, and were observed roosting in subalpine and mixed conifer forests, pinyon-juniper woodlands, mountain shrub highlands, and desertscrub benchlands and valleys. Several of these habitats are considered unsuitable for spotted owls due to their open character and the presence of potential predators (Gutierrez et al., 1995). The median final distance dispersed by owlets that left adult home ranges was 25.7 km; however, substantial variability in final dispersal distance was observed among the owlets (range = 1.68-92.3 km). Neither total distance nor final distance traveled during dispersal differed among the cohorts (ANOVA, $P = 0.115$ and 0.681 , respectively). Movement rates indicated that the juveniles initially moved rapidly away from the natal areas, but then began to slow down their movements and often settled on a winter home range by midwinter.

Table 2. Dispersal date, distance, and fate of selected radiotagged juvenile Mexican spotted owls. Owls with no dispersal date or distances died in the vicinity of the nest.

Owl Code	Dispersal Date	Last Live Location	Fate ¹	Final Dispersal Dist. ² (km)	Total Dist. ³ (km)
Ech474	1-Sep-92	15-Apr-93	Predation	21.2	189.9
Tw1873	5-Oct-92	5-Feb-93	Predation	10.6	39.7
Cam784	19-Sep-92	21-Nov-93	Radio died	26.5	187.8
Cam824	15-Sep-92	6-Feb-93	Exposure	43.6	97.1
Pea514		29-May-93	Exposure		
Ele915	26-Sep-92	24-Aug-93	Radio died	8.01	112.1
Ele574	5-Sep-92	29-Jun-93	Radio died	1.68	136.6
Tw1374	20-Sep-93	3-Mar-94	Exposure	15.1	40.9

¹ Fate indicated the outcome of tracking: signal loss occurred when owl transmitters could not be relocated after extensive search; radio molt referred to owls that dropped transmitters due to feather molt; Exposure referred to owls that were found starved to death; predation referred to owls that were killed by predators, although scavenging may have occurred.

² Final distance was estimated as the straight-line distance from the nest to the last observed location of an owl.

³ Total distance was estimated as the sum of the distance between all successive locations observed during dispersal.

Model Development for the GSENM

The statistical tools of ArcInfo GRID were used to create the Mexican spotted owl habitat model for southern Utah and explore the complex relationships between spotted owl locations, elevation, slope, slope curvature, geology, and vegetation themes. We used a multivariate analysis, including multiple regression, to perform a GIS classification with known samples. Essentially, this procedure used historic owl locations (i.e., recorded locations



where owls have been observed) and expert knowledge of unsuitable locations (i.e., terrain with little or no habitat architectural complexity, such as flat grass and shrublands, plateau and mesa tops). We identified two habitat categories: suitable breeding habitat and nonbreeding habitat (Howe et al., 1993; Rinkevich et al., 1995). The two habitat categories were used to classify thematic pixels into maximum-likelihood classes. The study area was modeled at the 1:500,000 spatial scale with the base topographic information derived from a digital elevation model (DEM). We assumed that suitable breeding habitat had an identifiable relationship with GIS themes that could not be identified without spatial analysis. We used the GIS model output to create a map layer predicting the distribution of breeding habitat in the study area (Figure 2).

Discussion

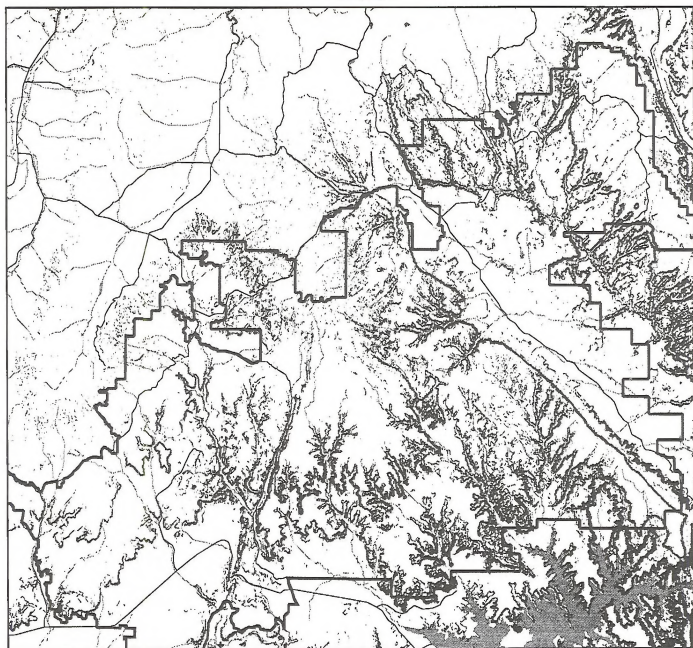
The association we detected between Mexican spotted owls and the relatively open canyon habitat highlights the importance of research along the fringe of a species range. The importance of the canyon habitat for spotted owls in the GSENM would not have been identified if traditional models of habitat preference had been applied (e.g., Hunter et al., 1995; Forsman and Giese, 1997; Grubb et al., 1997). Although spotted owls were not found in late seral forests, the sites located in Utah represented the most rugged portions of the landscape and support the idea that spotted owls occupy complex habitat (LaHaye et al., 1997; Ripple et al., 1997). We detected a strong association between Mexican spotted owls and habitats within the rocky canyons in southern Utah, and this should be directly transferrable to these location types within the GSENM. Rocky canyon habitat provides numerous rock cavities and ledges for roost and nest sites, as well as thermal and escape cover for both the adults and young. During winter, when ambient temperatures decreased, spotted owls were observed roosting in more open habitats, and several moved upslope into forested highlands. This suggests that factors related to temperature

sensitivity (Barrows, 1981) should prove important for spotted owl breeding habitat in the GSENM. Results from the home-range study and an investigation of habitat selection enabled us to create a habitat model that predicted the extent of potential breeding habitat in the GSENM using a GIS (Figure 2). Our model predicts that potential breeding habitat occurs throughout the Monument and is coincident with the distribution of steep canyon topography. Areas that include a high density of breeding habitat generally follow steep canyon corridors highlighting the importance of management areas including: Capitol Reef, Zion, and Canyonlands National Parks and the GSENM.

Management Considerations for the GSENM

The first step that staff of the newly established GSENM might take is to survey their lands for spotted owls. The model provided in this study presents a stratified sampling scheme that the Monument can use, thus saving survey costs and time. Random locations in those predicted areas with high probability of owl occurrence can be surveyed, then the density of owls extrapolated for the Monument. It is important to include in the sampling scheme marginal habitats and those areas where owls are not predicted to occur.

The strong association between spotted owls and steep canyon topography suggests that this environment should be carefully managed in the GSENM. Perhaps portions of the predicted high-quality breeding habitat within the Monument can provide areas that would serve as ecological baselines for future study (e.g., Arcese and Sinclair, 1997). It is possible to place conservation areas around active and historic owl locations. If this management strategy is chosen, those areas should include an amount of steep canyon habitat equal to the mean MCP home range determined in this



Legend

-  Breeding Habitat
-  Water Bodies
-  Rivers and Streams
-  Roads
-  Owl Locations
-  Grand Staircase-Escalante NM

SCALE 1:700000
5 0 10 20
MILES



Prepared by:
Daniel Spotskey
Cartographer
Grand Canyon National Park
and
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Biologist
Colorado Plateau Research Station
Northern Arizona University

Coordinate System: UTM zone 12
1927 North American Datum

Figure 2. Habitat model depicting potential spotted owl breeding habitat in the Grand Staircase-Escalante National Monument.



study, plus two standard deviations (two deviations theoretically will include most of the potential variation around the mean values determined). It is also possible to identify "protected activity centers" following recommendations of the Mexican spotted owl recovery plan (USDI 1995). Because we found that spotted owl home ranges were typically centered around nest and roost sites, we recommend that conservation areas (e.g., protected activity centers) be centered around known nest and roost sites.

In the canyonlands of the GSENM, potential threats to the spotted owl may include: increased human activities in remote canyonlands, petroleum and mineral development, inundation of habitat and reclamation, and impacts of livestock grazing on rodent communities (Howe et al., 1993; Arcese and Sinclair, 1997). Given the "threatened" status of the Mexican spotted owl, information is needed to develop ecologically based management and implement the recovery process (USDI, 1995; Miller, 1996). We believe that additional survey effort is needed to locate spotted owl sites for protection and help validate predictive models of their habitat. Until surveys are conducted in the GSENM, reliable estimates of the population size within this Monument will not be available, nor will realistic estimates of long-term population viability be possible for the southern Colorado Plateau ecoregion. Once the survey work is completed, it would be useful for the Monument staff to develop a design for population monitoring in order to track changes in population size and provide estimates of viability.

Continued studies are needed on the habitat ecology of spotted owls in the GSENM, particularly on the relationship between spotted owls and prey. The primary prey captured by spotted owls in Utah was woodrats (*Neotoma* spp.) and deer mice (*Peromyscus maniculatus*) whose ecology is relatively unknown in the canyonlands region (USDI, 1995). The presence of spotted owls in the canyonlands could be related to prey availability and the habitat affinities of woodrats. Studies of winter habitat

use and annual prey should also be conducted across the Monument.

If spotted owl research in the GSENM is coordinated with recovery needs, the outlook for spotted owls in southern Utah will be quite good. Because the owl inhabits terrain that is relatively free from human disturbance, threats to breeding habitat are minimal, and potential threats could be controlled by management planning, e.g., limiting visitor back-country use of breeding areas during April-July each year. Potential breeding habitat should be protected following guidelines in the recovery plan for the Mexican spotted owl (USDI, 1995). Finally, education of back-country users within the GSENM canyon country areas will help humans accept camping and hiking restrictions in the context of protecting an important and threatened wildlife resource.

Acknowledgments

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ECOLOGY







Impacts of Trampling Soils in Southeast Utah Ecosystems

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Most arid and semiarid lands of the United States have been heavily impacted by human use since the late 1800's. Historically, most of this impact has been from livestock grazing near areas with forage and water. More recently, substantial increases in off-road vehicle and hiking activity have greatly expanded direct and indirect human impacts, both spatially and temporally. The combination of recreational use and livestock grazing is resulting in unprecedented levels of local and regional disturbances.

Many resources in arid ecosystems are sensitive to compressional and shear forces associated with current uses. Soils in arid regions are often highly erodible, and soil formation is extremely slow, taking 5,000 to 10,000 years or more (Dregne, 1983a). Low levels of organic matter, large particle size ranges, and shallow soil freezing depths generally found in these soils result in compactible soils with slow dilation rates. Compaction of soils results in less water infiltration and less locally available water (Webb, 1983; Wilshire, 1983), which in turn influence soil biota activity, nitrogen (N) cycle dynamics (Torbert and Wood, 1992), vascular plant vigor and reproduction (Crawford, 1979; Skujins, 1984) and decomposition rates

ABSTRACT

■ Soil stability and normal water and nutrient cycles in desert systems are critical in maintaining sustainable ecosystems, and are often disrupted by trampling by livestock and people and by off-road vehicle use. Soil compaction and flattening can result in decreased water infiltration. Disturbance of cryptobiotic soil crusts can lead to increased albedo with possible decreased precipitation, accelerated soil loss through wind and water erosion, and decreased diversity and abundance of soil biota. In addition, nutrient cycles can be altered through lowered nitrogen and carbon inputs and slowed decomposition of soil organic matter, resulting in lower nutrient levels in associated vascular plants. Ecosystems within the Monument are especially vulnerable due to the paucity of surface rooting vascular plants for soil stabilization, lower numbers of nitrogen-fixing higher plants, and lower soil temperatures which slow nutrient cycles. Recovery of desert soils from surface disturbance can be slow, leaving systems vulnerable to degradation. Recovery from compaction and decreased soil stability is estimated to take several hundred years. Reestablishment rates for soil bacterial and fungal populations are not known. Recovery rates of soil's nitrogen fixation capability is at least 50 years. Recovery of crusts can be hampered by large amounts of moving sediment, and reestablishment can be extremely difficult in some areas. Given the sensitivity of these resources and slow recovery times, soil and nutrient cycles in the Monument's ecosystems are at high risk from many user groups.

of soil organic matter (West, 1981). Soil aggregates and pore space, which are important for soil stability, for infiltration, and as microenvironments for soil biota, are reduced by compaction (Dregne, 1983a; Stolzy and Norman, 1961). Surface cyanobacterial-lichen soil crusts are also impacted by soil surface disturbance. In the western United States, these crusts are important for increased soil stability, water infiltration, and fertility of soils (Belnap and Gardner, 1993; Belnap and Gillette, in press a, b; Harper and Marble, 1988; Johansen, 1993; Metting, 1991). Absence of these crusts can lead to increased erosion, resulting in loss of organic matter, fine soil particles, nutrients, and microbial populations in soils (Harper and Marble, 1988; Schimel et al., 1985).



Normal nutrient cycles in these semiarid regions can also be disrupted by soil surface disturbance. Nitrogen is often limiting in desert systems (Zak and Whitford, 1988). Cyanobacterial-lichen soil crusts have been shown to be the dominant source of nitrogen in a cold-desert pinyon-juniper and a grassland ecosystem in southern Utah (Evans and Ehleringer, 1993; Evans and Belnap, in press). Experiments have demonstrated that all types of surface disturbance tested dramatically decreased nitrogenase activity in these crusts (Belnap et al., 1994). Plants growing on undisturbed sites consistently show higher N content when compared to adjacent disturbed sites (Belnap and Harper, 1995; Harper and Pendleton, 1993).

Cyanobacterial-lichen soil crusts are also an important source of fixed carbon for these sparsely vegetated areas (Beymer and Klopatek, 1991). In addition, soil disturbance can alter soil food webs and thereby affect nutrient availability in these systems (Ingham et al., 1989). Disruptions of soil food webs can reverberate throughout the ecosystem, affecting macrofloral and faunal components (Hendrix et al., 1992; Coleman et al., 1992). Plant community composition and architecture can also be affected by soil surface disturbance. Changes in these critical habitat components have been shown to affect invertebrate and vertebrate populations (MacMahon, 1987).

Materials and Methods

Study Sites

■ **Arches National Park:** Arches is located approximately 16 km north of Moab, Utah at 1370 m elevation. Rainfall is approximately 200 mm annually. A heavily trampled area was compared with an adjacent, relatively undisturbed area. Both sites are on Arches loamy fine sand with similar depth, slope, inclination, and exposure. The dominant vegetation is *Coleogyne ramosissima* (blackbrush). Plant interspaces in the untrampled area are covered with well-developed cyanobacterial-lichen crust.

■ **Behind-the-Rocks:** Situated on Rizno fine sandy loam at 1400 m, this site is located 15 km south of Moab, Utah. Rainfall is approximately 200 mm annually. This site is dominated by *C. ramosissima*. Undisturbed soils are covered by a cyanobacterial crust similar to that at the Arches untrampled site.

■ **Natural Bridges National Monument:** The Monument is located 73 miles southwest of Moab at 1980 m elevation. Annual rainfall is approximately 300 mm. A trampled site was compared to an area 200 m away that had received little trampling. Both sites are on Rizno fine sandy loam of similar depth, slope, inclination and exposure, dominated by *Pinus edulis* and *Juniperus utahensis*.

■ **Canyonlands National Park:** Located 31 miles south of Moab at 1513 m elevation, these two study sites are in adjacent grasslands. Both have sandy loam soils (Mido and Begay) with similar soil depth, slope, exposure. Both sites are dominated by the grasses *Stipa hymenoides* and *S. comata* (Kleiner and Harper, 1977). Rainfall averages 180 mm annually.

Analyses

Five randomly located transect lines were placed in each area at the Arches study site. Ground and vegetation cover were estimated with twenty 0.25-m² quadrats per transect using a nested frequency quadrat frame, Daubenmire cover classes, and density counts. All perennial plants were mapped. For those shrubs intersecting the transect line, distance from nearest neighbor and hummock height was estimated. Hummock height was estimated as the height at which a rod held parallel to the surface from the base of the shrub intersected a rod held vertically at the lowest point in the interspace between the considered shrub and its nearest neighbor.

Plant tissue elemental content was determined from composite samples comprising at least five individuals of each species. Analysis was done by the Brigham Young University Soil Laboratory. Nitrogenase activity in cyanobac-



terial crusts was determined by methods outlined in Belnap (1992, 1994). Soil biota were sampled at 0-10 cm, the depth at which maximum bacterial, fungal, and nematode biomass was found. Nematodes, total and active bacteria, microarthropods, and total and active fungal biomass were evaluated following methods outlined in Ingham et al. (1989).

Soil physical characteristics were determined for cores 0-10 cm deep. Soils were analyzed by the Brigham Young University Soils Laboratory. Soil depth was determined with a metal probe. Compaction was measured with a recording penetrometer and bulk density measurements. Soil temperatures were taken midday on five occasions between June and July 1994. Measurements were taken with a 1-mm-wide probe inserted just under the soil surface. Results were analyzed using analysis of variance (ANOVA), Duncan's multiple range test, and unpaired t-tests.

Results and Discussion

Soil Physical Characteristics

Soils at the trampled and untrampled sites in Arches were very similar (Table 1). Percent clay, silt, and organic matter were low at both sites and did not differ significantly. There were no statistically significant differences in zinc, iron, manganese, copper, total nitrogen, potassium, magnesium, or sodium levels. There were small, but significant differences in pH and percent sand. There were larger, significant differences in phosphorus (P) and calcium.

Bulk density and soil porosity were compared in the two areas. Bulk density was found to be significantly higher at 0-3- and 3-6-cm depths in the trampled area than in the

Table 1. Soil physical characteristics of disturbed and undisturbed areas at Arches National Park.

	Undisturbed		Disturbed		Significant Differences
	Mean	Std. Dev.	Mean	Std. Dev.	
pH	8.30	0.00	8.20	0.00	p<0.03
% Sand	82.23	0.80	85.76	0.70	p<0.05
% Clay	8.83	0.50	7.24	0.80	
% Silt	8.96	0.02	7.00	1.50	
% OM	0.55	0.14	0.40	0.30	
ppm P	34.04	0.14	44.38	0.08	p<0.01
ppm Zn	0.40	0.10	0.50	0.14	
ppm Fe	19.90	0.26	26.50	0.13	
ppm Mn	3.20	0.17	4.30	0.08	
ppm Cu	0.20	0.00	0.20	0.00	
ppm N	591.70	47.10	558.30	23.60	
ppm K	90.00	0.71	110.00	14.10	
ppm Ca	4390.00	99.00	3445.00	7.10	p<0.02
ppm Mg	70.00	0.00	70.00	0.00	
ppm Na	90.00	7.10	110.00	14.14	
0-3 cm BD	104.9	4.4	114.9	10.0	p<0.007
3-6 cm BD	99.5	4.9	108.1	5.6	p<0.001

untrampled area. Soil porosity was not significantly different at 0-3-cm depth between the two areas, but was significantly lower at 3-6-cm depth in the trampled area when compared to the untrampled area. Increasing bulk density often results in lower microbial populations and lower activity levels (Torbert and Wood, 1992). In addition, increased bulk density generally results in less water infiltration and increased runoff (Webb and Wilshire, 1980; Loope and Gifford, 1972). Decreased water availability locally can lead to increased water stress for plants, thereby accelerating desertification processes (Dregne, 1983b).

Soil Surface Cover and Cyanobacterial-Lichen Soil Crusts

At the Arches site, soil surfaces were compared between the trampled and untrampled sites (Table 2). Cover of plant litter, lichens, mosses, and cyanobacteria was significantly higher in the untrampled area. The untrampled area had 32 percent litter cover, contrasted with only 8 percent litter cover in the trampled area. While six species of lichens and four species of cyanobacteria were found in the untrampled area, only one species of



Table 2. Biological characteristics at Arches National Park in disturbed and undisturbed areas. All differences are statistically different at $p < 0.05$, except for frequency of litter, which was not significantly different.

	Undisturbed		Disturbed	
	Mean	Std. Dev.	Mean	Std. Dev.
Percent cover				
Cyano	45.50	7.20	78.20	14.10
Lichen	2.00	1.20	0.20	0.30
Collema	4.40	2.40	0.60	0.70
Moss	32.70	5.50	4.40	4.00
Litter	31.80	5.00	8.60	3.20
Bare ground	0.06	0.13	8.36	12.20
Exotics	0.06	0.13	1.40	1.30
Grass	3.56	1.48	2.38	0.95
Shrub	29.81	16.48	29.53	9.99
Frequency				
Lichen	0.36	0.15	0.02	0.02
Collema	0.76	0.05	0.14	0.15
Moss	0.95	0.04	0.31	0.24
Bare ground	0.03	0.05	0.88	0.06
Grovel	0.08	0.15	0.50	0.40
Grass	0.64	0.17	0.39	0.13
Shrubs	0.81	0.25	0.49	0.21
Community				
# of shrubs	7.20	1.24	3.20	0.58
Festuca weight, g	0.80	0.16	1.68	0.33
# of shrub species	2.30	0.50	1.40	0.55
Interspace, cm	43.00	4.95	41.31	5.09
Hummock height, cm	11.11	1.26	25.19	1.97
# of exotics	0.30	0.50	1.40	0.55
# of plant species	8.00	1.20	10.00	1.40

cyanobacteria was found in the trampled area. Lichens and mosses combined covered 39 percent of the surface in the untrampled area; in trampled areas, they covered 4 percent. Lichen and moss species had a combined frequency four times greater in the untrampled than the trampled area. Trampled interspace surfaces were generally flat, whereas untrampled interspace surfaces supported cyanobacterial pedicels up to 7 cm high.

Litter and cryptobiotic crust cover and roughened microtopography play important roles in protection of soil surfaces from water and wind erosion, and in enhanced water infiltration. The combination of litter, vascular plant, lichen, and moss cover, left virtually no surfaces exposed to wind or water erosion in the untrampled area, whereas most of the interspaces in the trampled area had little, if any, protec-

tion. Surfaces trampled flat promote sheet erosion. Untrampled, pedicelled surfaces create microcatchments for water and reduce velocity of surface water flows, thus encouraging suspended sediments to settle out (Harper and Marble, 1988). Consequently, trampling can greatly accelerate desertification processes through increased soil loss and water runoff (Dregne, 1983b).

As cyanobacteria move through the soil, they leave behind polysaccharide material that firmly adheres to soil particles, even when dry or no longer associated with a living cyanobacterium (Figure 1). Sheath material can absorb up to eight times its weight in water, increasing the water-holding capacity of the soil (Brock, 1975; Campbell, 1979; Campbell et al., 1989). In addition, nutrient-rich clay particles adhere to sheath material, thus increasing the fertility of soils (Belnap and Gardner, 1993; Belnap and Harper, 1995). Soil crusts can also affect higher plant seedling establishment and survival. Experiments with fine

and coarsely textured soils demonstrated that seedling establishment was higher for forbs and grasses in crusted areas than uncrusted areas. Survival over a 3-year period was enhanced in two species and unaffected in one species. Overall plant survival was three times higher in the crusted plots (Belnap, 1994). Other studies have reported similar enhancement of seedling germination and establishment in crusted areas when compared to noncrusted surfaces (Harper and Marble, 1988; St. Clair et al., 1986; Lesica and Shelley, 1992).

Surface disturbance has been shown to negatively affect the cohesion and coverage of cyanobacterial crusts, since crustal components are brittle when dry and easily crushed (Belnap, 1993; Campbell et al., 1989; Harper and Marble, 1988). Surface disturbance also reduces the depth to which abandoned

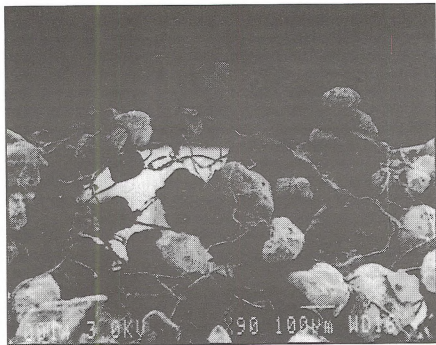


Figure 1. A scanning electron micrograph of dry cyanobacterial sheaths winding through sandy soils from Maab, Utah. Note firm attachment of sheath material to the individual sand grains, even though sheath material is dry (magnification $\times 90$).

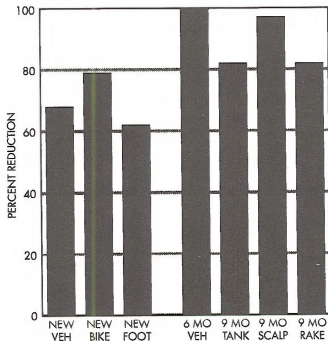


Figure 2. Percent reduction of nitrogenase activity after soil surface disturbances were experimentally applied. All differences from the control were significant. Bike, vehicle, and footprint treatments were applied near Maab, Utah; tank, rake, and scalped treatments were applied at Dugway Proving Ground, Utah (Belnap et al., 1994).

cyanobacterial sheath accumulates, thereby reducing resistance to water erosion. At many disturbed sites, sheath material is often not observed below 1 mm depth, in contrast to 7-cm-thick crusts in untrampled areas. Consequently, impacts to surface crusts can reduce soil stability, soil fertility, and soil moisture retention, thus accelerating desertification in impacted areas (Dregne, 1983b).

Cyanobacteria and cyanobacterial components of soil lichens fix atmospheric nitrogen (Belnap, 1992; Skujins and Klubek, 1978; West and Skujins, 1977; Terry and

Burns, 1987). Studies have demonstrated that nitrogen fixed by soil cyanobacteria is available to neighboring vascular plants under laboratory conditions (Mayland et al., 1966; Mayland and McIntosh, 1966). In some desert systems, these crusts have been demonstrated to be the dominant source of this often-limiting element (Evans and Ehleringer, 1993).

Nitrogenase activity was dramatically reduced in soil crusts regardless of the type of experimentally applied disturbance (Figure 2) (Belnap et al., 1994; Belnap, 1996). Disturbance by human feet, mountain bikes, four-wheel drive trucks, tracked vehicles (tanks), and shallow and deep raking all resulted in an immediate 40-80 percent reduction in nitrogenase activity. Measurements at 6-9 months posttreatment showed that nitrogenase activity had dropped still lower in the disturbed areas, with treatments showing an 80-100 percent reduction (Belnap et al., 1994). At the Arches trampled site, no nitrogenase activity could be detected, while the undisturbed site showed normal nitrogenase activity. Because disturbance generally increases



nitrogen losses through enhanced denitrification and accelerated soil erosion (Peterjohn and Schlesinger, 1990), less nitrogen input often results in less total nitrogen for the ecosystem. Reduced fertility of systems is one of the most definitive, and problematic, aspects of desertification (Dregne, 1983b).

Soil Food Webs

Biomass of active bacteria, total bacteria, active fungi, and total fungi, as well as nematode numbers, were measured in paired trampled and untrampled areas in Arches and Natural Bridges National Park units. Results obtained from the two areas were similar. At Arches, the biomass of active bacteria was over three times higher in the untrampled area compared to the trampled area (Table 3). Total bacterial biomass was higher in the trampled area, whereas active and total fungal biomass was not significantly affected by disturbance. The ratio of total fungi to bacteria was significantly shifted in the trampled area by a factor of two, with relatively more bacteria present there. Nematode populations were significantly affected as well (Table 4). Numbers of bacterial and fungal feeding

Table 3. Active and total bacterial and fungal biomass at Arches National Park and Natural Bridges National Monument. AB = Active bacteria; AF = Active fungi; A/TB = Active/total bacteria; A/TF = Active/total fungi; TB = Total bacteria; TF = Total fungi; TF/B = Total fungi/bacteria. Asterisk (*) denotes statistical differences at $p < 0.05$.

	AF	TF	AB	TB	TF/B
Arches undisturbed	0.3±0.2	14.5±5.5	2.3±1.0*	3.78±0.82*	4.0±1.4*
Arches disturbed	0.4±0.5	11.6±4.9	1.2±0.7*	5.35±1.6*	2.5±1.7*
Natural Bridges undisturbed	0.59±0.67*	25.2±7.7	0.8±0.35*	3.4±0.6*	7.5±2.4*
Natural Bridges disturbed	0	31.5±24.5	0.12±0.14	14.2±4.8*	3.1±3.6*

nematodes in the untrampled area were twice those found in the trampled area. Numbers of plant root feeders were not significantly different. Total nematode numbers in the untrampled area were twice that of the trampled area.

Soil biota was also analyzed at Natural Bridges National Monument (Tables 3 and 4), and results similar to Arches were obtained. Biomass of active bacteria and fungi was six to seven times higher in the untrampled area when compared to the trampled area. Total bacterial biomass was three times higher in the trampled area, while total fungal biomass was not significantly different. The ratio of fungi to bacteria was significantly shifted in the trampled area by a factor of three, with relatively more bacteria in the trampled area. Nematode numbers were significantly affected as well, with numbers of bacterial and fungal feeders seven to ten times higher in the

Table 4. Nematode populations at Arches and Natural Bridges National Park. Total numbers, bacterial feeders, and fungal feeders were significantly higher in the undisturbed area ($p < 0.05$). Numbers of root feeders were not significantly different.

	Bacterial feeders	Fungal feeders	Root feeders	Total individuals
<i>Nematode functional groups</i>				
Arches undisturbed	505.0±287.0*	97.0±142.0*	35.0±38.0	651.0±646.0*
Arches disturbed	370.0±287.0*	54.0±127.0*	67.0±54.0	493.0±360.0*
Natural Bridges undisturbed	36.12±33.56*	30.09±44.0*	4.08±9.5	70.44±82.65*
Natural Bridges disturbed	5.02± 2.85*	2.81± 2.71*	0.07±2.52	8.56± 4.9*



untrampled area. Plant root feeders were not significantly affected. Total nematode numbers were almost seven times greater in the untrampled area than in the trampled area.

Microarthropod populations were compared between trampled and untrampled areas in Canyonlands National Park. Although released from grazing 30 years ago, numbers of individuals of each species were still higher in the untrampled area, both under plants and in plant interspaces, than in the disturbed area (Table 5). Total individuals were over three times more abundant (44 vs. 18) under shrubs of the untrampled as opposed to the trampled area. In shrub interspaces, individuals were seven times as abundant (1 vs. 7) in the untrampled as the trampled area. In the grass community, the same pattern was observed. Individuals were almost three times as abundant in the untrampled area under grass plants (14 vs. 5) than the trampled area. Microarthropod individuals were 1.4 times more abundant (10 vs. 7) in the untrampled interspace between grasses than in trampled interspaces. Total numbers of individuals found in the untrampled area were double that observed in the trampled area (72 vs. 34). Fewer species were found in trampled than untrampled areas in both shrub (11 vs. 15 species) and grass (7 vs. 11 species) communities. The results represent a decline in species richness of 26 percent and 36 percent, respectively. Four species found in the trampled area were not found in the untrampled area, and six species from the untrampled area were not found in the trampled area.

Soil food webs can profoundly influence nutrient availability in ecosystems, and changes in soil biota populations can result in slower decomposition rates and less nutrients available to plants, thereby hastening the

desertification process. Nutrient uptake rates can be affected by the ability of bacteria to solubilize and/or chelate elements (Lange, 1974). Symbiotic fungi can increase a plant's ability to exploit more soil volume, as well as increasing spatial distribution of carbon in soils. Carbon- and nitrogen-fixing soil microbiota contribute to site fertility. Larger microbial populations mean greater retention of N, P, and other nutrients bound up in microbial biomass (Skujins, 1984). Bacteria are known to secrete IAA and other plant growth regulators. Both bacteria and fungi secrete polysaccharide material that acts to aggregate soil particles (Lange, 1974). The presence of bacteria and fungi can also affect vascular plant root morphology (Skujins, 1984).

Ratios of microbes vary in different systems. Shrub-dominated systems generally have relatively higher fungal numbers to decompose more recalcitrant woody litter, while grass systems have relatively more bacteria. Disturbance often shifts these ratios. Both the blackbrush community at Arches and the pinyon-juniper community at Natural Bridges resulted in stimulation of bacterial activity, and a depression in fungal activity. Since different soil biota process litter differently, such a shift in soil food web structure or relative activity levels can significantly lower litter decomposition rates, lower nutrient availability to systems, and thus increase desertification rates.

Predators, such as nematodes and microarthropods, are an essential part of the soil food web as well. These organisms play important roles in decomposition cycles by shredding litter, mixing soil layers, and carrying litter underground. They act as dispersers of other soil microorganisms. They can modify soil pH and

Table 5. Microarthropods: numbers of microarthropods in a never grazed and a previously grazed site in Canyonlands National Park. No statistical analyses were done on these samples.

	Shrub total species	Grass total species	Shrub canopy	Shrub interspace	Grass canopy	Grass interspace	Total individuals
<i>Microarthropods</i>							
Undisturbed	15	11	44	7	14	10	72
Disturbed	11	7	18	1	5	7	34



contribute N, P, and other nutrients to soils through fecal material and release of nutrients bound up in microbial biomass. They also influence soil food web structure through preferential predation on other soil organisms. Lowering of microarthropod numbers, and alteration of population structure, can significantly lower decomposition rates, and again accelerate the desertification process (Zak and Whitford, 1988; Santos and Whitford, 1981; Seastedt and Crossley, 1984; Kitchell et al., 1979).

Nutrient Levels in Vascular Plants

Concentrations of nitrogen and other macronutrients in annual, biennial, and perennial plants were found to be significantly higher when the plants were growing on undisturbed crusted surfaces compared to on adjacent trampled areas at all study sites tested (Figure 3). At Arches, leaf tissue N in the untrampled area was 9 percent higher in the perennial shrub *Coleogyne*, 31 percent higher in the perennial forb *Streptanthella*, and 13 percent higher in the annual grass *Festuca*. Leaf tissue content of N in the biennial *Mentzelia multiflora* was higher in plants growing in a crusted area relative to plants from an adjacent sand dune at a nearby site in Arches (Belnap and Harper, 1995). The same results were obtained at other field sites around Utah and in greenhouse experiments, where levels of nitrogen in sorghum and rape were higher in pots with cyanobacteria when compared to pots without cyanobacteria. Dry weights of plants in pots with cyanobacteria were up to four times greater than in pots without cyanobacteria (Harper and Pendleton, 1993). Dry weights of *Festuca* plants in the untrampled area were two times those of plants in the trampled area (Belnap and Harper, 1995).

Maintaining normal nitrogen cycles is critical to maintaining the fertility of semiarid soils and to preventing desertification (Dregne, 1983b). After water, nitrogen is generally considered the element most likely to limit primary productivity in semiarid and arid ecosystems (Ettershank et al., 1978; Romney et al., 1978).

Vascular Plant Community Structure

Plant community composition and structure were examined at the Arches trampled site and compared to a nearby untrampled area, and many significant differences were observed. Fewer larger individuals of the dominant shrub *Coleogyne ramosissima* were found in the trampled area when compared to the untrampled area. Shrubs dominated the interspace of the undisturbed area, whereas annuals or perennial bulbs (with aboveground parts only in the spring) dominated the

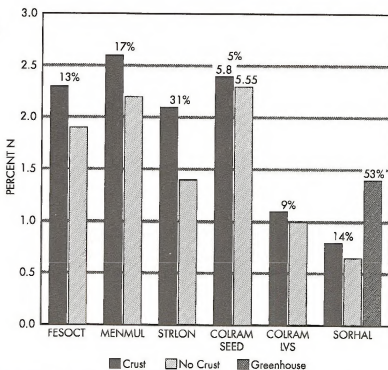


Figure 3. Nitrogen levels in vascular plant tissue from sites around the State of Utah, USA. Plants were collected from adjacent crusted and uncrusted soils. All differences were statistically different at $p < 0.05$. FES OCT = *Festuca octoflora* (annual grass); MEN MUL = *Mentzelia multiflora* (annual forb); STR LON = *Streptanthella longirostris* (perennial forb); COL RAM = *Coleogyne ramosissima* seedlings and leaves (perennial shrub); SOR HAL = *Sorghum halpensis* (annual grass).



interspace in the trampled area. Exotic grasses contributed significantly to grass cover in the trampled area, whereas the untrampled area had only a few exotic plant individuals.

Interspaces between *Coleogyne* plants were significantly larger and hummocks under the shrubs were four times higher in the trampled area when compared to the untrampled area. Consequently, more soil is exposed to erosion in the trampled area. In addition, small animals face crossing an average of 4.8 m between *Coleogyne* plants in the trampled area, compared to 2.0 m in the untrampled area, resulting in higher exposure to predation. The trampled area also had only small annual plants in the interspaces, instead of perennials such as *Opuntia polyacantha* that might offer additional protective cover. Changes in plant community architecture has been shown to affect populations of invertebrates and vertebrates living in these communities (MacMahon, 1987). As a result, trampling may have many as yet undocumented effects on semiarid and arid landscapes that increase their susceptibility to desertification.

Surface Albedo and Temperature

Albedo is also of concern in semiarid and arid systems. When trampled surfaces were

compared to untrampled surfaces, there was up to a 50 percent increase in reflectance from 0.25 to 2.5 μm (Figure 4). This represents a change in the surface energy flux of approximately 40 watts/m^2 (Roger Clark, USGS, pers. comm.) Large acreages of trampled areas, combined with lack of urban areas to offset this energy loss, could lead to changes in regional climate patterns in many semiarid regions (Sagan et al., 1979).

Concomitant with albedo changes, trampled surfaces had significantly different surface temperatures than untrampled surfaces. Midday temperatures were taken in June and July, 1994. Air temperatures were found to average 39°C (S.D. 0.25°C), bare sand 52°C (S.D. 0.5°C), and dark crusted surfaces 62°C (S.D. 1.0°C). These differences were all significant. In the winter, surface temperatures of well-developed crusts were up to 14°C higher than ambient air temperature.

Surface temperatures can be very important in desert systems. Nitrogenase activity is heavily temperature-dependent, with lower temperatures resulting in lowered activity levels (Rychert et al., 1978). Altered soil temperatures can be expected to affect microbial activity, plant nutrient uptake rates, and soil water evaporation rates. Soil temperatures have been shown to affect seed germination time and seedling growth rates for vascular

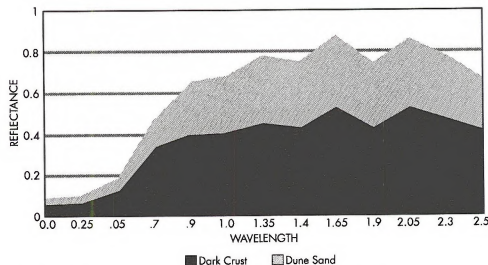


Figure 4. Reflectance of bare sand and *Microcoleus*-dominated soil surfaces. Measurements were done using a laboratory spectrophotometer. (From Gregg Swayze and Roger Clark, USGS).

plants. Timing of these events is often critical in deserts, and relatively small delays can reduce species fitness and seedling establishment, which may eventually affect community structure (Bush and Van Aiken, 1991). Food and other resources are often partitioned among ants, arthropods, and small mammals on the basis of surface-



temperature-controlled foraging times (Doyen and Tschinkel, 1974; Crawford, 1991; Wallwork, 1982). Many small desert animals are weak burrowers, and soil surface microclimates are of great importance to their survival (Larmuth, 1978). Consequently, altering surface temperatures can affect nutrient availability and community structure for many desert organisms, thus increasing susceptibility to desertification.

Recovery from Surface Disturbance

Some work has been done to estimate recovery rates of soil disturbances in arid systems. Recovery of soils from compaction has been estimated to require 100-130 years in the Great Basin (Knapp, 1992) and 80-140 years in the Mojave Desert (Webb and Wilshire, 1980). Recovery rates of soil biota are expected to be slow, given slow recovery of soil porosity, moisture-dependent microbial activity in a dry environment, limited dispersal ability, naturally low microbial populations, and large disturbance areas.

Much more is known about the recovery rates of cyanobacterial-lichen soil crusts. Recovery rates have been found to depend on the type and extent of disturbance, on the availability of nearby inoculation material, as well as on the temperature and moisture regimes that follow disturbance events. Estimates of time for visually assessed recovery have varied from 5 to 100 years (Anderson et al., 1982; Jeffries and Klopatek, 1987; Callison et al., 1985; Cole, 1990). However, Belnap (1993) showed that many components of recovery cannot be assessed visually. Assuming linear recovery rates, recovery was estimated to be 35-65 years for cyanobacterial biomass, 45-85 years for lichen cover, and 250 years for moss cover in scalped 0.25 m² plots surrounded by well-developed crusts. Since recovery time is dependent on presence of nearby inoculant, larger disturbed areas will take longer to recover. Several studies have demonstrated that inoculation can hasten the biological recovery of disturbed crusts (Tidemann et al., 1980; Ashley and Rushforth, 1984; Belnap, 1993).

Nitrogenase activity recovery appears to be quite slow. In scalped areas, no nitrogenase activity was detectable after 9 years, and N content of soils was still much lower when compared to adjacent control plots. In areas disturbed with four-wheel drive activity, no recovery could be documented after 2 years (Belnap, 1996). Using isotopic ratios of N, soil and plant N and nitrogenase activity levels were found to be significantly lower in an area that had been released from livestock grazing for 30 years when compared to an area that was never grazed. These data suggest that negative effects on nitrogen dynamics may persist in systems for extended periods of time after disturbance ceases. This slow recovery from disturbance indicates that this system is vulnerable to desertification.

Restoration of normal surface albedos and temperatures will depend on the restoration of cyanobacteria, lichens, and mosses. While cyanobacteria form a dark matrix in which other components are embedded, dark mosses and lichens contribute up to 40 percent of the cover in an undisturbed crust (Belnap, 1993). Consequently, recovery of surface albedo characteristics in severely disturbed areas could take up to 250 years for even very small areas.

Different deserts may show very different resistance and resilience to surface disturbances. Some characteristics of deserts suggest that these ecosystems probably evolved with low levels of soil surface disturbance by ungulates. These characteristics include the presence of cryptobiotic soil crust, the morphology and phenology of perennial bunch grasses found in these deserts, and the dominance of C₃ grasses (Mack and Thompson, 1982). Some deserts, such as those found in the Colorado Plateau biogeographic province, may have also evolved with low levels of microdisturbance such as those created by soil and surface invertebrates, and thus depend more heavily on soil surface integrity for natural ecosystem functioning. As a result, these deserts may be more negatively affected by soil surface disturbances than deserts that evolved with higher levels of surface disturbance.



Conclusion

Thirty percent of the landscapes in the United States are semiarid or arid. Preventing desertification of these areas requires maintaining the sustainability and productivity of the ecosystems contained within these areas. Because most current land use practices involve extensive impacts to soil surfaces, it is critical that we understand the short- and long-term effects of such impacts on nutrient cycles and soil food webs in these ecosystems. It is apparent from the data presented here that nutrient cycles in deserts can be extremely sensitive to soil surface disturbances. Nitrogen cycles may be at the greatest risk from current land use practices. Input of available nitrogen from atmospheric and parent material sources is extremely low in arid regions, and these systems are generally dependent on biologically fixed nitrogen and nitrogen released from the decomposition of organic matter. The above data indicate that both of these input pathways are threatened by soil surface disturbances. Because nitrogen loss is a continuous process, understanding factors that decrease the input or availability of nitrogen is of critical importance to maintaining the sustainability of arid systems (Peterjohn and Schlesinger, 1990).

Preventing soil loss is another major challenge in these areas. Many semiarid and arid areas rely on soil surface cyanobacteria for stability, and current land uses are impacting large acreages of this resource (Belnap, pers. obs.). In addition, loss of diversity of processes and species results from current types of soil surface disturbance. The sensitivity of the semiarid and arid lands of the western United States to these impacts, combined with the low resiliency of these systems, indicate that they are at risk. In managing these areas, it is important to conserve the fertility and stability of soil resources.

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Geocology of the Hanging Gardens: Endemic Resources in the GSENM

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ABSTRACT

■ Hanging gardens are isolated mesophytic communities that are physically and biologically distinct from surrounding xerophytic and riparian communities. The hanging gardens of the Colorado Plateau are distributed in an "archipelago" of individual "island" habitats, largely within the drainage system of the Plateau. Unique geomorphology created by ground-water sapping can be detected remotely and used to anticipate the occurrence of this habitat (May, 1995; May et al., 1995).

A really extensive, relatively flat-lying sedimentary rocks dissected by the greater Colorado River drainage system characterize the Colorado Plateau physiographic province. Several transmissive sandstone units on the Plateau are effective aquifers (Taylor and Hood, 1988) underlain by relatively impermeable strata acting as aquitards. Where erosional processes expose the contact between aquifers and aquitards, ground water may exit as seeps and springs. Hanging gardens occur where ground-water seeps provide a perennial, nonfluvial water supply for mesophytic, nonriparian vascular plants. Geomorphology resulting from a process called "sapping" is common on the downside of broad dip planes in plateau sandstones (Laity and Malin, 1985). Ground-water sapping creates a protective geomorphology for the hanging garden habitat.

The National Park Service supported research in seven park units of the Colorado Plateau from 1990-1993 (Stanton et al., 1991, 1992a,b). While the actual sites included in the analyzed data all occur in Park units, the scale of the project was Plateauwide, from the Virgin River watershed in the southwest to

Hanging gardens are "endemic" to the Colorado Plateau based on their prevalence in and peculiarity to the ubiquitous sandstone aquifers of this physiographic province. Based on geocologic parameters that occur in the GSENM, hanging gardens are likely to be distinctive, abundant, and impact-sensitive in the Monument (May, 1997). Hanging gardens support high endemism in their invertebrate and vascular plant populations (Fowler et al., 1995). This resource merits consideration and management as an endemic ecosystem in the GSENM (Estill and May, 1996).

the Green and Yampa watersheds in the northeast. May developed a simple, descriptive, and predictive classification of the geomorphology of the hanging garden habitat, which was tested and refined throughout the 3-year endeavor (May et al., 1995). A conceptual model of the geocologic contingencies of hanging garden occurrence and persistence evolved from this initial geomorphologic description and classification (May, 1995). The model, and the hanging gardens of the Plateau, are used as an illustration of the contributions that geocologic modeling based on contingency may make to land and resource management (May, 1997; Estill and May, 1996).

The hanging garden *habitat* is contingent upon the two geomorphologic parameters mentioned above: a perennial, seep-delivered water supply, and the protective geometry created



by ground-water sapping. These two conditions are necessary, but not sufficient to result in the occurrence and persistence of the hanging garden vascular plant *species assemblage*. The biotic elements of the hanging garden ecosystem are contingent on the ecologic requirements, biogeographic history, and dispersal characteristics of individual species. Together, these abiotic and biotic interdependencies are the *geoeologic contingencies* that determine the occurrence, distribution, and persistence of hanging gardens. The sequence and pattern of colonization and interspecific interactions become site-level contingencies that determine the unique character of individual hanging gardens.

The physical parameters that govern the occurrence of hanging gardens can be detected remotely. A combination of geological maps that show surficial outcrops of rock types and subregional scale structure and topographic maps that show canyon and cliff face geometry can yield a strongly reliable prediction of the probable occurrence of ground-water seeps. Examination of more than 200 drainages in National Park units and elsewhere on the Plateau confirmed that ground-water seeps are more likely than not to support hanging garden species assemblages. This fortunate fact allows an indirect anticipation of the occurrence of the seven vascular plant species that occur only on hanging gardens, and of the eleven Colorado Plateau endemic vascular plant species supported on hanging gardens (Fowler et al., 1995). May and Rorick (1996, unpublished) successfully applied the geoeologic model to predict hanging garden species assemblage occurrence in the Shawnee National Forest of Missouri.

Understanding the physical parameters that control habitat occurrence and persistence also allows habitat-based management for the conservation of endemic species. Microhabitats (see below) can be disturbed past their ability to support their contingent of garden species by any activity that promotes erosion of colluvial soil or disrupts the flow of ground water to the seep zone. The ability to anticipate where hanging gardens will occur, and what

processes can disturb and/or destroy them, has obvious implications for the management plan of the Grand Staircase-Escalante National Monument. Applying the geoeologic model would be a cost-effective and reliable means of targeting areas for inventory and monitoring of both the hanging garden communities and the endemic species they support.

Geology, Ground-Water Sapping, and Geomorphology

"The finest workers in stone are not copper or steel tools, but the gentle touches of air and water working at their leisure with a liberal allowance of time."

Henry David Thoreau

Geology

The geologic history of the Colorado Plateau as a physiographic province is unique and incompletely understood. The timing of its uplift, and the tectonic forces responsible, continue to be studied by geologists. The Plateau has acted as a physically cohesive unit, behaving independently during Sevier-style compressional tectonism and tectonic expansion of the Basin and Range province, and falling outside the areas affected by Laramide-style crustal deformation. The Plateau has been topographically high since long before its rotation into its current position in the intermountain west. Though warped by broad anticlines, monoclines, and synclines, and everywhere fractured, faulted, and jointed, the flat-lying sedimentary units of the Plateau have remained remarkably undeformed by the changes wrought all around them by plate motions of the last 70 million years. Consequently, the major physical attributes shaping the Plateau landscape are erosional features. The canyons of the Colorado Plateau are largely the unique natural artistry of moving water—both on the surface and through the rocks of the Plateau itself.



Ground-Water Sapping

Many of the cliff-forming rock units of the Plateau are sandstone units, deposited by wind (e.g., the Navajo Sandstone), streams and floodplain dynamics (e.g., the sandy parts of the Kayenta Formation or the Cedar Mesa Sandstone), and even near-shore marine depositional regimes (e.g., parts of the Carmel Formation). Most of these sandstone units hold water (i.e., are aquifers), but the primary aquifer sandstones of the southern Plateau are the wind-deposited (aeolian) Wingate, Navajo, and Entrada Formations. These rocks are, over much of their areal extent, lithified sand dunes. The structure and shape of the preserved dunes are still visible. The weathering characteristics of these ancient dunes create much of the aesthetic beauty of the canyon country's harmonious arched landforms. Fluvially deposited rocks, which are generally finer grained and less transmissive than the coarser grained sandstones above them, underlie the Wingate and the Navajo, as well as the Entrada in some places. This pairing of a coarser grained, sandy unit (facies) above a finer grained facies of siltstones, claystones, and mudstones creates an aquifer-aquitard couplet. While such a contact commonly occurs between formally identified rock formations, the relationship between coarse-grained and fine-grained facies also commonly occurs within an individual rock formation. Ground water moves downward through the more transmissive facies and is stopped when it reaches the less-permeable, fine-grained facies. Then it spreads laterally until it reaches another vertical conduit: a fault, joint, fracture, or the side of a canyon wall that has exposed the aquifer-aquitard contact. These simple controls on the movement of ground water, along with larger scale controls like the dip (angle relative to horizontal) of the rock unit itself, determine whether and where water will exit the aquifer as seeps and springs.

Springs are point-source water delivery phenomena, and create a fluvial (streaming) regime beneath them, however small or large they may be. Moving water is both an erosional and a depositional force. It entrains particles of

the rock and soil it moves over and carries them some distance before dropping its bedload as an *alluvial* deposit. Seeps, however, generally do not have a significant fluvial component. Rock at the face of a seep is slowly disaggregated mechanically and chemically as the cement holding particles together is dissolved, and/or the particles are pushed apart by crystal formation from minerals precipitating out of the ground water. When it can no longer hold itself together, the rock collapses and is deposited by gravity as a *colluvial* deposit. The distinction between springs and seeps, and between colluvial and alluvial soils, is not semantic; in fact, it is critical to understanding the physical parameters of the hanging garden habitat.

Springs are parts of fluvial (stream) regimes. Fluvial processes create a characteristic geometry and canyon growth pattern. Canyons formed by fluvial processes are v-shaped; i.e., wide at the top and narrow at the bottom. They are shallower and narrower at their heads than at their mouths. The position and direction of growth of fluvially formed canyons is heavily, sometimes wholly, controlled by topography and surface features of the landscape. Unless there is some major geologic structural control (or human-caused redirection), fluvial systems tend to be dendritic, with the number of tributaries increasing and their size decreasing headward into the source areas of the watershed.

Seeps are parts of ground-water regimes. Ground-water sapping also creates a characteristic geometry and canyon growth pattern (Laity and Malin, 1985). In contrast to fluvially formed canyons, those shaped by ground-water sapping are U-shaped with steep, straight sides and bottoms that are as wide as tops. They are frequently as deep and as wide at their heads as they are at their mouths. Such canyon headwalls have been referred to as "theatres," "amphitheatres," and even "glens" (John Wesley Powell, speaking of Glen Canyon). The position and direction of growth of ground-water-shaped canyons is determined primarily by subsurface controls on the flow of ground water; e.g., joint systems, faults, dip planes,



subsurface sedimentary features of the rock unit, and heterogeneity in the transmissivity of the rock unit. Some of these constraints may mimic, or even contribute to, the surficial controls on surface water movement, in which case ground-water and fluvial processes may be superimposed or may even interact. For the most part however, ground water moves independently of surface water.

Canyon growth by sapping may also be viewed as a developmental phase in overall downcutting and erosional regimes. That is, a degree of fluvial erosion must precede sapping in order for downcutting to expose a contact of the aquifer-aquitard couplet. And canyons growing by sapping may be succeeded in their depths by a fluvial system when downcutting reaches rocks that do not act as aquifers. Many Plateau canyons display this ontogenetic pattern in their geomorphology, with wide, slope-sided canyons at the top, steep, straight-sided canyons in the middle, and v-shaped active fluvial systems in the bottom. The geomorphology of the portion of a canyon that is growing by ground-water sapping, however, remains visibly and functionally distinct from fluvial systems above and below.

The sapping process occurs at seep faces, where water saturates the aquifer rock and disaggregates it as mentioned above. Canyon growth occurs as rock mass wastes (falls away from itself and downward) from seep zones on canyon walls. Canyons both widen and lengthen by ground-water sapping. Where seepage is relatively even laterally along a canyon wall, a single canyon continues to widen. Any concentration of ground-water flow will create more rapid headward-concave geometry, and eventually a new "tributary" or "branch" canyon grows off at an angle to the main canyon. The branches ("tributaries") of ground-water-shaped canyons occur asymmetrically; that is, they can only occur on the updip side of the canyon. The main canyon itself interrupts ground-water flow. If the rock on the updip side of a canyon has many parallel joints that intersect the canyon at an angle, ground-water flow that is directed by the joints will create a series of branches to the main canyon that are spaced

along the joints and are relatively equal in size (this is common in the highly jointed portions of the Navajo Sandstone). Thus, the addition of tributaries to a canyon growing by ground-water geomorphic processes does not follow the same rules of geometric increase in number and geometric decrease in size as stream piracy dissects a fluvially controlled watershed. In fact, it is rather difficult to call the branches of a ground-water-formed canyon "tributaries" at all, since there is not necessarily any more water diverted into the drainage through the addition of branch canyons. In the growth of a fluvial drainage system, the addition of tributaries increases the total volume of water moving through that watershed by subsuming adjacent drainages.

The large-scale pattern differences between canyon growth by ground-water sapping and canyon growth by fluvial processes are easy to pick out from topographic maps, aerial photographs, and even satellite imagery. This means that the likely occurrence of seep zones (in the heads, at least, of short, stubby, steep-sided canyons growing in an asymmetric and nongeometric pattern) can be detected through remote sensing. This is an important convenience for land and resource management, as discussed above.

Geomorphology

At the broad scale described above, the geomorphology created by ground-water sapping controls the broad distribution of the hanging garden ecosystem, and allows for a coarse level of anticipation of the occurrence of individual hanging gardens. That is, hanging gardens are likely to occur in canyons shaped by ground-water sapping, because they are likely to contain active seeps. At the site level of individual hanging gardens, this geomorphology is critically important to the occurrence and persistence of the habitat and the species assemblage that may occupy it.

The first criterion for the occurrence of a hanging garden is the seep. The vascular plant species that occupy the hanging garden habitat are mesophytic and require a perennial water



supply, but generally these are not riparian species. Where gardens are situated immediately above a stream or plunge pool, riparian species may occur where colluvial soils end and alluvial soils begin, but these two habitats are distinct, and the distribution of riparian species is usually limited to the true riparian zone. Likewise, the edge between surrounding xeric habitat and the garden habitat is generally quite distinct. Colluvial soils moistened by the seep support the mesophytic garden species and are too moist for the xerophytic species immediately adjacent; conversely, the dry colluvium off the garden will not support garden species.

The second criterion for the occurrence of a hanging garden is the protection provided by headward-concave geomorphology created by the sapping process at the seep. Overhead protection maintains the habitat within two of its threshold physical parameters: the absence of significant fluvial processes, and protection from excess insolation and aridity. Even a centimeter of overhead protection shields the garden habitat from precipitation and surface runoff that erode the unstable colluvial soil in which many garden species root. Even a centimeter of overhead protection from sun and wind creates a microclimate that is favorable to mesophytic species. Some canyons in the aeolian units of the Plateau contain hundreds of tiny, low-diversity (even monospecific) hanging gardens on small seeps that occur on fine-grained interdunal contacts. These seep-line gardens may exhibit almost undistinguishable headward-concave geometry, but there is always at least enough to allow a couple millimeters of colluvium to collect, and to throw a shade line at midday. At the other end of the spectrum, some of the hanging gardens researched in 1990-1993 are more than 300 meters in length, measured along the primary seep line, and the colluvial soil microhabitat extends up to 200 meters below the garden. Note that the concavity of the garden (i.e., the depth of overhead protection through headward erosion) must be sufficiently deep to protect the soil slope beneath from most precipitation and surface runoff. These deep gardens tend to occur in the heads of canyons

and in the aeolian units of the Plateau. The hanging garden above the Upper Emerald Pool in Zion National Park is a prime example. In sandstone units that are characterized by more horizontal bedding, gardens may be very long horizontally, but shallow in terms of both headward concavity and extent of colluvial soil beneath the seep line (again, these last two are directly correlated).

Microhabitats

May et al. (1995) use the term *microhabitat* to distinguish specific kinds of places within gardens from the hanging garden habitat as a whole. Each of three basic microhabitat types tends to support a characteristic suite of vascular plant species, and to vary in overall diversity. The following three microhabitats were identified: seep-line, wet-wall, and colluvial-soil. These may exist singly or in multiples within an individual hanging garden; that is, there may be one to many of each microhabitat on a single garden. The occurrence of the wet-wall and colluvial-soil microhabitats, however, is contingent upon the occurrence of the seep-line microhabitat.

The seep-line microhabitat is defined as a garden, regardless of its size or the presence of either or both of the other two microhabitats. Sapping-controlled canyons in the aeolian units of the Plateau may contain hundreds of individual seep-line gardens. Where the seep-line microhabitat exists alone, discharge is relatively low, a small volume of colluvium develops only at the contact between aquifer and aquitard, and there is insufficient discharge to maintain the wet-wall microhabitat. Plants root directly in the seep zone, which also supports bacterial colonization. Vegetation uses all available discharge that is not lost to evaporation. Garden species that can tolerate the driest conditions (e.g., *Petrophytum caspitosum*) tend to occupy seep-line gardens with low discharge. The seep-line microhabitat is linear. Some overhead protection, if only millimeters deep, is provided by the sapping process. Orientation of seep-lines is generally horizontal, though they may occur at any angle, including the vertical, if water is moving sufficiently



slowly through a joint or fracture (i.e., below the fluvial threshold). In aeolian aquifers like the Navajo Sandstone, the high-angle cross-bedding of ancient dunes creates planes of differential transmissivity that can perch water long enough for its exit as a seep. In such situations, garden vegetation occupies seeps with geometry that mimics the slip-face of the original sand dune.

Where discharge rates are higher, the seep-line is but one of the two or three microhabitats present. In these instances, garden species that are also found on the colluvial-soil and wet-wall microhabitats may also occupy the seep-line, and the edges between microhabitats can be indistinct. Where there are multiple seep-lines, they are generally stacked vertically, and one garden with a primary and one or many secondary seeps is identified. This situation commonly occurs in the heads of canyons growing by sapping.

Where there is sufficient discharge from a seep, water may flow across bare rock at slopes too steep for the accumulation of colluvium. This is the wet-wall microhabitat, exemplified by the giant weeping walls of Zion Canyon. The wet-wall microhabitat supports the clinging vascular plants commonly associated with the name and notion of a hanging garden, as well as algal and bacterial colonies and bryophytes. Vegetation roots directly in rock fractures or on small clumps of colluvium that accumulate on the irregular wet-wall face. Wet walls have a planar geometry that may be either concave or convex relative to the cliff face depending on site-specific geological structure. They are oriented at angles above 65 degrees and may even be supervertical. Discharge may be sufficient to surpass the fluvial threshold on portions of wet walls. Where this occurs, erosion of disaggregated material at the seep face occurs and the microhabitat is sparsely colonized. Wet-walls are subject to seasonal perturbation by ice shear in some parts of the Plateau.

The colluvial-soil microhabitat supports both the greatest diversity and abundance of garden species (Stanton et al., 1992b). This microhabitat

occurs as soil develops through direct weathering of parent rock. The parent rock may be the supporting ledges of the fine-grained aquitard facies, or the colluvium, which is gravity-deposited as the sapping process loosens aquifer rock at the seep face, and is generally a combination of both. Colluvial deposits on hanging gardens range in size from individual sand, silt, and clay grains to massive sections of the cliff face that spall off when headward erosion removes underlying support. Obviously, these larger mass-wasting events are episodic perturbations of the geoeologic system. Apparently, the homeostatic mechanisms of the geoeologic system prevail even through large mass-wasting events. The timing and pattern of recovery is a potential area for formal study by those interested in geoeologic processes of complex natural systems.

The colluvial soils on hanging gardens are not well-studied, and no formal description of soil profiles exists. They tend to be high in sand content, though the finer grained parent rock of the aquitard facies contributes a varying proportion of clay. These soils tend to be highly to totally saturated by seep discharge. They are moistened laterally and from beneath by wicking, but are generally protected from precipitation and other overhead sources. Slow drips from overhanging seep lines generally do not result in fluvial processes on the colluvial slope.

The colluvial-soil microhabitat may have a triangular or planar geometry, depending on the lithology and structure of the aquifer and aquitard facies. Triangular, concave-headward geometries occur in aeolian aquifers, and planar geometries occur when gardens form in rocks with strongly horizontal bedding structure. These geometries are further discussed below. The colluvial-soil microhabitat is oriented anywhere from the horizontal up to about 65 degrees. The steep slope of many colluvial-soil microhabitats is above the normal angle of repose of its constituent grains. These saturated soils are held at abnormally steep angles largely through colonization by bacteria and algae that holds grains together in a colloidal fashion. This "colloid" of disaggregated



grains and its organic component can hold colluvium at the seep face at vertical and even supravertical angles. Colonization of disaggregated rock by algae and bacteria at the seep face can be laminar and resembles stromatolitic substrate-cyanobacterial growth.

Saturation of colluvium, whether sandy or clay-rich, makes it highly unstable, especially at the steep slopes characteristic of hanging gardens. Whatever stability is conferred by the root systems of vascular plants is easily overcome by even minor disturbance, including human or livestock foot traffic or erosion by fluvial processes. In fact, wherever the discharge of the seep surpasses the fluvial threshold, colluvium is eroded. Some high-discharge gardens have small rivulets of runoff coursing through a colluvial soil slope and collecting in plunge pools below or joining perennial or intermittent streams. Alluvium generally does not accumulate in the rivulets, as slopes are too steep, so any material entrained by the fluvial process is removed from the garden. The fragility of the colluvial-soil microhabitat creates the primary physical parameters governing garden colonization, persistence and character. As mentioned above, the overhead protection conferred by headward-concave geometry makes ground-water sapping one of the geoeologic contingencies of hanging gardens.

Geomorphologic Classification

Hanging gardens may be described in terms of their geometry and the microhabitats present. This implies relative discharge rate of the seeps and the sedimentologic origin of the aquifer and aquitard facies. A geomorphologic classification describes none of the biotic elements of the ecosystem, though it may predict guild structure functionally. A geomorphologic classification serves to minimize physical variability that does not relate to biological variation. Teasing apart physical and biological variation is critically important to any research that examines biogeographic distributions, as well as to studies of community convergence and divergence (e.g., Samuels and Drake, 1997).

May et al. (1995) use a first-order classification of hanging gardens as either *simple* or *complex*. *Simple* hanging gardens are seep-line gardens, comprising this habitat alone. *Complex* gardens comprise at least one seep-line plus either or both the wet-wall and colluvial-soil microhabitats. Complex gardens may contain one or many patches of any of the three microhabitats.

The second order of the classification is based on overall geometry. *Simple* gardens have a linear geometry, as described above. *Navajo-type complex* gardens have an overall triangular geometry. These tend to be strongly concave inward on both perpendicular and horizontal planes. They occur primarily in aeolian sandstones characterized by cross-bedding structure. The differential weakness along highly angled planes causes rock to weather and mass-waste at angles other than the horizontal. When support is removed from beneath aeolian rocks by either fluvial or ground-water processes, it tends to collapse along planes that correspond with the original slip faces of sand dunes. This angle is relatively uniform (between 29 and 31 degrees) due to homogeneity of sand grain size and shape in the aeolian units of the Colorado Plateau. The harmonious and ubiquitous arched landforms characteristic of the Plateau landscape are testimony of rock weathering and breaking at this angle. This weathering characteristic creates the generally triangular/conical geomorphology of hanging gardens that occur in aeolian rocks. These are named *Navajo-type complexes* after one of the largest aeolian units on the planet. *Navajo-type complexes* usually exhibit strong lateral control on seep zones by jointing or other localized structural controls on ground-water concentrations. They are frequently deeply roofed, and the downward tapering of the colluvial soil slopes corresponds to the shape of overhead protection.

Cedar Mesa-type complexes are again named for a geological formation that exemplifies the sedimentary origin and lithology of aquifers that yield hanging gardens with a tabular morphology. These complexes occur in sandstone units that have strong horizontal bedding



structures. Seep lines may extend laterally for long distances; there is weak lateral control on ground-water flow. Colluvial soil slopes are long and shallow, do not taper downward, and exhibit strike-parallel concave-headward geometry. The extent of headward erosion determines the relative depth of the colluvial-soil microhabitat down slope from the seep line; that is, overhead protection delimits the vertical extent of this microhabitat. *Cedar Mesa-type complexes* do not exhibit concave-headward geometry on the perpendicular plane, except at drainage headwalls.

Hanging Garden Species Assemblages and Biogeography

A full description of the biotic elements of hanging gardens is beyond the scope of this paper and outside of this author's expertise. I limit this section to a brief discussion of some interesting biogeographic patterns that are relevant to the utility of geocologic thought models in both basic and applied research on complex natural systems. For a thorough review of the biological aspects of hanging garden vascular plant occurrence and vegetation ecology, I refer the reader to the work of Fowler (1995; Fowler et al., 1995), Stanton et al. (1991, 1992a,b), Tuhy and MacMahon (1988), Welsh (1984, 1989a,b), and Welsh and Toft (1975, 1981).

Fowler (1995) found that of the 201 vascular plant species identified on 84 hanging gardens, 11 are endemic to the Colorado Plateau and 7 are endemic to hanging gardens (see also Welsh 1984, 1989a,b; Welsh and Toft, 1975, 1981). One additional species of *Erigeron*, found only on one garden in Capitol Reef National Park, appears to be new to science and extremely restricted in range. Fowler et al. (1995) discuss the distribution of endemism on hanging gardens, finding that it is relatively higher in the central portions of the Colorado Plateau than on its periphery (e.g., in the

Virgin River watershed and the Green and Yampa watersheds). Such a pattern adds weight to the argument that Colorado Plateau and hanging garden endemics may be the result of speciation events associated with insularity of disjunct habitats. The biogeographic affinity of many Plateau endemics is with source areas off (and some quite distant from) the Plateau or Basin and Range, which argues against "refugia" hypotheses for their current disjunct distribution. Any biogeographic or evolutionary inquiry into the distribution of the biotic elements of hanging gardens requires that physical differences among gardens be normalized or discounted so that current variations in environmental attributes do not conflate historical or biological evidence.

Fowler also found evidence supporting equilibrium-based hypotheses of species-area relationships for "virtual islands" (MacArthur and Wilson, 1963, 1967; Simberloff, 1976). That is, "The largest hanging gardens have high species richness and lower dominance values while the smaller hanging gardens have low species richness and high dominance values" (Fowler, 1995). Fowler found that area alone explained 44 percent of the variance in species richness among 84 hanging gardens. While this pattern is certainly significant, the underlying causes may be different than those invoked by deterministic, equilibrium notions wherein an "optimal" diversity will be achieved in any system given sufficient time and opportunity. The size of hanging gardens is directly related to their age. As sapping continues, habitat is literally carved out of a cliff face. The longer a garden exists before some extrinsic factor resets or truncates its ontogeny (e.g., a major mass-wasting event, drying up or diversion of seep supplies, or fire) the more time is available for immigration and successful colonization. There is no evidence of an equilibrium end point to garden growth and diversity increase. If there is a limit to garden size, the constraints are geological and hydrological, not biological. Therefore, corresponding diversity increase is likely to be due to linear temporal dynamics, not a theoretical "optimal equilibrium." Neither is there evidence that the trajectories of species assemblages will be the same if



reset; in fact, some evidence suggests the contrary. All aboveground vegetation was burned after fireworks ignited a very hot fire on a hanging garden in Knowles Cañon in the Glen Canyon National Recreation Area in 1989. The plant community had been described previously (Welsh, 1984), so changes in species composition can and have been monitored as the garden recovers from this extreme resetting event (Graham, 1997). Of the 24 species that have successfully recovered (from surviving rootstock) or recolonized this garden, only 10 occurred there before the fire. Unless assembly rules for hanging garden species are somehow ecologically locked so that, given enough time, the garden will reacquire its prefire taxonomic composition, it is likely that the trajectory of this garden's assemblage will diverge from its previous state. Hanging gardens are sufficiently dissimilar across their entire range and from one drainage to the next (Fowler, 1995) to make such ecologic convergence unlikely. Again, there is no evidence for an equilibrium end state for the system as a whole, or as individual hanging gardens. The hanging gardens system is a perfect natural laboratory for examining community convergence versus divergence (see review in Samuels and Drake, 1997). Again, the relatively conservative physical variation described by a geocologic model allows one to "hold constant" or to discount that potential source of biological variation—a critical consideration for such research.

Fowler did not find that habitat complexity, measured as the number of microhabitat patches

on a single garden, was statistically significant in explaining species richness. However, this statistic masks the effect of early ontogenetic stages in habitat development, and of complexity differences between microhabitats. Species richness on complex (having at least two microhabitats singly or multiply) gardens is higher than on simple (seep-line microhabitat only) gardens. Species richness is also higher whenever the colluvial-soil microhabitat is present, versus the relatively low diversity effect of the addition of the wet-wall microhabitat. The colluvial-soil microhabitat is more complex (heterogeneous) than either the wet-wall or the seep-line microhabitat. During the early ontogeny of an individual hanging garden, species richness will increase as either or both the wet-wall and colluvial-soil microhabitats are added through geomorphic processes. An increase in diversity seems to correspond to a predicted increase in physical complexity (analogous to evolutionary radiations into empty ecospace) (Erwin, 1992) when examined at appropriate temporal and hierarchical scales.

Fowler (1995) placed hanging garden species assemblages into five classes, based on statistical gaps in similarity indices. He named these five classes for their dominant and codominant species as determined by percentage canopy cover. All gardens that did not fall into these classes were statistically dissimilar from one another and from each class. Drainages sampled in each of the National Park units researched have gardens that fall into Fowler's classes as follows:

Dinosaur NM:

Reedgrass
Columbine

Capitol Reef NP:
Fern

Canyonlands NP:

Reedgrass
Columbine

Archae NP:
Fern

Columbine
Fern-Columbine

Zion NP:
Fern
Fern-Thistle
Reedgrass

Glen Canyon NRA:
Fern
Fern-Thistle
Reedgrass
Columbine

Natural Bridges NM:
Fern

Reedgrass
Columbine



The sampling areas on the previous page are arranged so as to crudely mimic the geographic distribution of the "J-shaped" archipelago of hanging garden "islands" on the Colorado Plateau (obviously this is congruent with the incised drainage of the greater Colorado River system). Even at this coarse level, interesting north-south and east-west geographic trends are apparent.

Also interesting, but by no means fully examined, are within-genera species distributions, and in several cases within-family species distributions. For instance, the columbines *Aquilegia chrysantha* and *A. formosa* occur in Zion only, among sampled areas, while in all other sampling areas only *A. micrantha* occurs. *A. micrantha* is a hanging garden endemic; the other two columbines have distributions off the Colorado Plateau. Only the orchid *Epipactis gigantea* occurs in Zion; all other sampled areas show the occurrence (frequently together) of *E. gigantea* and the Colorado Plateau endemic orchid *Habenaria zothecina*. The thistle genus *Cirsium* occurs in all sampled areas. In Zion, the species present include *C. neomexicanum* var. *utahense* and *C. arizonicum*, neither of which occurs in the other sampled areas. In Dinosaur, at the other extreme of the hanging gardens archipelago, only *C. oumbeyi* occurs, and again it does not occur elsewhere in the system. The hanging garden endemic thistle *C. rydbergii* occurs in the middle of the archipelago, in Glen Canyon, Arches, and Canyonlands. North and west of this concentration of *C. rydbergii* (which can comprise up to 82 percent of the canopy in Glen Canyon), only the thistle *C. calcareum* occurs in Capitol Reef. South and east of the *C. rydbergii* concentration, in Natural Bridges, *C. undulatum* occurs most frequently (with occasional occurrences of *C. calcareum*) and does not occur in the other sampled areas. Of the family Scrophulariaceae, the monkey flowers *Mimulus cardinalis* and *M. guttatus* occur only in Zion among sampled areas. In the same family, the paintbrush *Castilleja scabrida* var. *scabrida* also occurs only in Zion. At the other end of the archipelago, in Dinosaur only *C. linariifolia* represents the Scrophulariaceae. The family is not represented in the Natural Bridges outlying area. In the middle of the

archipelago, the hanging garden endemic monkeyflower *Mimulus eastwoodiae* occurs in all samples.

Such within-genera and within-family species distributions suggest convergence (increased similarity) of the hanging garden vascular plant assemblage above the species level. In many other instances, "functional analogs" trending across the geographic distribution of the hanging gardens system were observed. These patterns suggest that investigating the hanging gardens system at several hierarchical and taxonomic levels (Valentine and May, 1996), including that of functional subguilds, might offer tests of convergence versus divergence and equilibrium versus nonequilibrium dynamics of complex natural systems.

The fact that dissimilar species assemblages frequently occur closely spaced in the same sampling area, while occupying geomorphologically identical hanging gardens and comprising functional analogs of one another, suggests two things. First, the physical parameters of the geoecologic model are at too inclusive a level to capture physical variations responsible for species distributions. Second, each garden is colonized in a species-specific manner with time of arrival and incumbency effects shaping a unique niche-partitioning trajectory during each garden's ontogeny. Both possibilities are likely contributors to the organizing dynamics of gardens. Incumbency effects seem likely to inhibit immigration of congeneric species after a certain developmental window in garden colonization.

Corroboration of the strength of incumbency is indicated by the apparent resistance of hanging gardens to invasion by noxious species. Only 2 of 84 sampled gardens had been invaded by tamarisk. *Tamarix ramosissima* is a notorious invader throughout the drainage system of the Plateau. No garden had been invaded by Russian thistle, also an opportunistic invader in Plateau watersheds. The two gardens that had been invaded by tamarisk are two of the most highly human-disturbed gardens in the sample: "Pyro" in Glen Canyon is the garden that was burned to the ground by



fireworks (see above), and "Weeping Rock" in Zion, which suffers the most human foot traffic of any garden in the sample. While apparently resistant to invasion, hanging gardens are sensitive to local extirpation due to the instability of colluvial soil slopes and the absolute dependence on seep discharge. This fragility of habitat, combined with strong self-reinforcement dynamics for organization at and above the generic level, creates an immensely intriguing system for basic research on the structure of complex systems. Likewise, the same questions and hypotheses are critically important to land and resource management science. Understanding the geoeologic contingencies of this fragile habitat can aid conservation of (especially) endemic species. Investigating and understanding the resistance of hanging gardens to invasion by noxious species could be very helpful in the battle against that epidemic in the West.

Hanging Gardens in the Grand Staircase-Escalante National Monument

The geographic area of the GSENM converges on areas researched by Fowler and May between 1990 and 1993. A preliminary assessment based on topographic and geologic maps at 1:500,000-scale suggests that the geoeologic parameters necessary for garden occurrence exist within the Monument. Areas that appear most likely to contain hanging gardens are: the reaches of the Escalante River and its tributaries that occur within the Monument; all margins of the Kaiparowitz Plateau, particularly its southern border, and many of its drainages in the south and west; and the White Cliffs, Johnson Canyon, and Johnson Lakes Canyon of the Grand Staircase district. Assessment based on closer application of the geoeologic model to geologic quadrangles and smaller scale topographic maps would yield a significantly tighter target area for ground-level inventories.

Basic Research

Adding information on the hanging gardens of the GSENM to the database developed by Fowler (1995) and using it to further refine the geomorphologic classification and geoeologic model of May (1995; May et al., 1995) would add considerably to the strength of statistical analyses of the biogeography of the whole hanging gardens system. The simple increase in sample size that would accrue by adding the gardens of the GSENM would improve statistical strength by itself. However, as shown above, trends in species distributions among the previously sampled areas suggest that gardens in the middle of the trends are critical tests for any biogeographic hypotheses. Future research planned by this author on the evolutionary ecology and nonlinear dynamics of the whole hanging gardens system will certainly require geoeologic and taxonomic information from the gardens in the GSENM.

Applied Research and Management Goals

Basic research on hanging gardens can and should yield information that is useful and accessible for both the planning effort and future management of the GSENM. Conversely, applied research at the level of inventory and monitoring can and should yield information useful to scientists interested in the complex dynamics and history of the hanging gardens system. Given that a thorough methodology for examining the ecology of the vascular plant and invertebrate communities was developed by the National Park-supported research of Fowler, May, and Stanton, it seems prudent to suggest that the same methodology be applied to assessment, inventory, and monitoring of the hanging gardens in the Monument. The data yielded could be easily and thoroughly incorporated into the database and geoeologic model already constructed at the Plateau scale. Given also that adjacent lands cooperation in resource stewardship will be an important element of the Monument strategy, using the methodology applied by adjacent land managers would be prudent on the part of the GSENM.



Summary

The hanging gardens of the Colorado Plateau are an unparalleled natural laboratory for basic research in ecology, evolution, biogeography, and particularly, the cutting edge of research in complex systems dynamics. Hanging gardens support endemic species, and their management as whole habitats, according to a geoeologic model of physical threshold parameters, can be a cost-effective and reliable conservation strategy. The GSENM is likely to contain abundant, distinctive, and impact-sensitive hanging gardens. They are likely to occur in all three districts of the Monument. The planning effort and management of the GSENM should consider hanging gardens explicitly and support research that provides a reliable estimate of the relative importance of this endemic resource in the Monument. Such an assessment should be based on the methodology employed by the Plateau-scale research supported by the National Park Service, and the resulting information shared with all adjacent land managers.

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Burning Coal Seams in the Grand Staircase-Escalante National Monument: A Natural System for Studies of Plant Responses to Elevated CO₂

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ABSTRACT

■ Our limited understanding of long-term ecosystem responses to rising atmospheric CO₂ concentrations has led to an interest in natural CO₂ vents and springs that could serve as low-cost experimental settings for understanding how ecosystems might respond in the future. In the Burning Hills and Smoky Mountains of the Grand Staircase-Escalante National Monument, a number of exposed coal deposits have been ignited by lightning and have been burning for periods of years to centuries. We examined one of these sites where the belowground combustion of low-sulfur coal releases CO₂ and other gases to the atmosphere. Our interest was in evaluating the potential of these vent sites as natural field experiments for studying the influence of elevated atmospheric CO₂ on the growth of desert vegetation. Both instantaneous measurements of CO₂ concentration (made with an infrared gas analyzer) and long-term, integrated measurements (using the carbon isotope ratio of the continuously distributed C₄ vegetation) showed that atmospheric CO₂ concentrations decreased with distance from the most active vents. Measurements of the carbon isotope discrimination by C₃ vegetation, which tends to dominate the landscape, indicated that photosynthetic gas exchange rates were significantly altered by elevated CO₂. Water-use efficiency of the vegetation was doubled under elevated CO₂. Given the notable effects of the increased CO₂ levels on both C₃ and C₄ vegetation, the burning vents in the GSENM could serve as excellent, inexpensive natural laboratories for examining ecosystem-level responses of arid lands to elevated CO₂ concentrations.

Atmospheric CO₂ concentration is steadily rising, and based on the current input rate, present levels are expected to double by 2100 (Watson et al., 1990). There is little doubt that this change in atmospheric CO₂ will have potentially dramatic impacts on plants at all ecological levels, including increases in plant productivity, changes in plant community composition, and shifts in ecosystem functioning.

Our understanding of the ecosystem impacts is limited for several reasons. Much of the previous work on the effects of increased CO₂ concentrations has been conducted under artificial conditions in greenhouses and growth chambers. Few of the experiments have allowed one to evaluate how species interact under elevated CO₂. As the next logical step in understanding how elevated CO₂ will affect



plants, tremendous scientific effort is currently underway with CO₂ fumigations of vegetation in the field; the most common approach involves the Free-Air CO₂ Enrichment (FACE) plots where an entire patch of an ecosystem is surrounded by pipes that elevate and control the CO₂ concentration within the ecosystem (Hendrey, 1993). These experiments, which require large amounts of money and effort, yield new and interesting results that often contrast with limited greenhouse pot studies (Körner and Miglietta, 1994). However, our understanding is still in its infancy; it will take years before the effects of these fumigations on long-lived plants, such as trees and shrubs, and on long-term impacts to processes like biogeochemical cycling and food web structures that may ultimately control community composition shifts, are understood. Ecosystems may not be equally impacted by increased atmospheric CO₂ concentrations due to variability of natural resource limitations (Mooney et al., 1991). From early FACE results and modeling studies, it appears that aridland ecosystems may be very sensitive to elevated CO₂ (Neilson, 1995; Field et al., 1997). This is an indirect effect associated with elevated CO₂ causing a partial closure of stomata, which limits transpiration and allows plants to remain active longer into the drought period.

Given the limits to our understanding of the effects of increased atmospheric CO₂ concentrations on natural ecosystems, it is not surprising that a keen scientific interest has developed in natural CO₂ vents and springs (Raschi and van Gardingen, 1997). Around the world, geothermal CO₂ springs and burning coal vents, some of which have been active for hundreds of years, are now being investigated as potential low-cost, field laboratories for studying long-term effects on natural ecosystems (see Raschi and van Gardingen, 1997). A number of coal vents are currently burning in the Smoky Mountains and Burning Hills of the Grand Staircase-Escalante National Monument (GSENM). Doelling and Graham (1972) described these as coal deposits which underlie existing sandstone, and frequently outcrop at the surface. Occasionally the coal

deposits at the surface are ignited by lightning, resulting in underground fires. The vents in GSENM, several of which have been burning for many years, release CO₂ and other gases into the atmosphere. Not only are CO₂ concentrations of the air increased around these vents, but the carbon isotope ratio ($\delta^{13}\text{C}$) of the CO₂ evolved is significantly different from that of normal atmospheric CO₂, serving as a tracer to quantify local atmospheric CO₂ concentrations. Gleason and Kyser (1984) reported that the $\delta^{13}\text{C}$ of CO₂ released from one of the burning coal sites was -32.5 parts per mil (‰), which is significantly more negative than atmospheric values, which tend to be near -8‰. Because atmospheric CO₂ is the source for plant photosynthesis and plant growth, the CO₂ released from this coal combustion had the potential to impact the $\delta^{13}\text{C}$ values of vegetation at distances of up to 700-800 m from the vent system investigated.

Our objective for this study was to quantify the CO₂ concentrations and evaluate, through stable isotope analysis, the potential of these vent sites to serve as natural field experiments for studying the influence of elevated atmospheric CO₂ conditions on the growth of desert vegetation. Stable isotope analysis is a valuable tool because the isotopic composition of plant material reflects that of the CO₂ that was the source for photosynthesis, integrated over the life of that particular plant tissue. It also serves as a measure of plant water-use efficiency. We had two questions in this study. First, could long-term average, atmospheric CO₂ concentrations be reconstructed from the isotopic values of the surrounding vegetation? Second, could we observe the ecophysiological effects of increased CO₂ on members of the plant community?

The plant community surrounding these coal vents is cold-desert vegetation, consisting of both C₃ and C₄ shrub and perennial herb species (Caldwell, 1985; West, 1988; Comstock and Ehleringer, 1992). Limited vegetation change has occurred, except in the disturbed areas immediately adjacent to a burning vent.



The $\delta^{13}\text{C}$ values of vegetation were analyzed to quantify CO_2 concentration and plant ecological responses. The carbon isotope ratio of C_4 plants was examined to answer the first of our two questions. This is because under most atmospheric CO_2 concentrations, the changes in leaf $\delta^{13}\text{C}$ will reflect the changes in atmospheric $\delta^{13}\text{C}$ values. In C_4 plants, initial carboxylation is by phosphoenolpyruvate carboxylase (PEPC), which discriminates very little against ^{13}C . Because of the high PEPC activity, the drop in CO_2 concentration between the air and the intercellular spaces within the leaf is small and constant. Farquhar (1983) modeled the carbon isotope ratio of C_4 plants as:

$$\delta^{13}\text{C}_{\text{plant}} = \delta^{13}\text{C}_{\text{air}} - a - (b_i - b_p\phi - a) c/c_i \quad (1)$$

where $\delta^{13}\text{C}_{\text{plant}}$ is the carbon isotope ratio [‰ relative to the Pee Dee Belemnite (PDB) standard] of the plant sample, $\delta^{13}\text{C}_{\text{air}}$ is the carbon isotope ratio of the CO_2 in the atmosphere (typically -8‰ in a nonenriched atmosphere), a is the fractionation associated with the slower diffusion of $^{13}\text{CO}_2$ air (-4.4‰), b_i is the net fractionation associated with PEP carboxylation (-5.7‰), b_p is the net fractionation associated with Rubisco (27‰), ϕ is the proportion of carbon fixed by PEP that subsequently leaks out of the bundle sheath, and c_i and c_a are the intercellular and atmospheric CO_2 concentrations, respectively (Farquhar et al., 1982). The sum $(b_i - b_p\phi - a)$ is a small number, further reduced by its product with the c/c_i ratio. If changes in the c/c_i ratio are limited and the other parameters remain constant, then changes in $\delta^{13}\text{C}_{\text{plant}}$ must be a result of changes in $\delta^{13}\text{C}_{\text{air}}$.

The $\delta^{13}\text{C}$ values of C_3 plants were examined to answer the second of our two questions. This is because in C_3 plants the c/c_i ratio changes significantly in response to water stress. The c/c_i ratio, and therefore $\delta^{13}\text{C}_{\text{plant}}$, becomes a measure of plant water-use efficiency. According to well-accepted theory, these $\delta^{13}\text{C}$ values are influenced by the isotope ratio of the source air, fractionation steps between the bulk atmosphere CO_2 and the initial photosynthetic reaction by RuBP carboxylase

(Rubisco), and by the drop in CO_2 concentration between the air and the intercellular spaces within the leaf. The factors influencing C_3 leaf carbon isotope ratios can be described as:

$$\delta^{13}\text{C}_{\text{plant}} = \delta^{13}\text{C}_{\text{air}} - a - (b_i - a) c/c_i \quad (2)$$

Taken together, the terms $(-a - (b_i - a) c/c_i)$ are the discrimination (Δ) against ^{13}C by the leaf and represent the change in ^{13}C content between the atmosphere and fixed carbon in the leaf.

Given this, it is likely that, at least within a species, the $\delta^{13}\text{C}_{\text{plant}}$ value of C_4 plants can be used to estimate the $\delta^{13}\text{C}_{\text{air}}$ if we assume that other parameters in Equation 1 are constant. Evans et al. (1986) and Henderson et al. (1992) provided initial evidence in support of this assumption. Marino and McElroy (1991) and Marino et al. (1992) have adopted this approach and used it to estimate $\delta^{13}\text{C}_{\text{air}}$ over historical time periods, although it is possible that some environmental influences could affect carbon isotope discrimination by C_4 plants (Henderson et al., 1992). There is evidence that soil salinity can influence carbon isotope discrimination by C_4 plants (Walker and Sinclair, 1992; Sandquist and Ehleringer, 1994; Leffler et al., 1997), but drought does not appear to have any impact (Leffler et al., 1997). The $\delta^{13}\text{C}_{\text{plant}}$ value of C_3 plants, which is a measure of c/c_i , is considered a key parameter in plant gas exchange (i.e., CO_2 uptake and water loss), and indicates a metabolic set point that relates the constraints imposed by water and nutrient limitations (Ehleringer, 1993).

By measuring the carbon isotope discrimination of plants on nonsaline sites at varying distances from one of the burning coal seam vent sources, we examined the possibility that atmospheric CO_2 concentrations could be reconstructed from C_4 isotopic values and that these vents might serve as a tool for investigating elevated CO_2 effects on ecophysiological activity of C_3 and C_4 species in this desert community. Atmospheric gases were also analyzed with an infrared gas analyzer to compare with isotopic observations.



Materials and Methods

Study Site

Field observations were made in August, 1994 on an isolated, unnamed peak in the Burning Hills of southern Utah, USA (lat. 37°16', long. 111°22', 1750 m elevation). The coal seam on this peak had been burning for an extended period (>25 years) and was very near the site described by Gleason and Kyser (1984). We sampled vegetation at varying distances from a series of coal vents burning at the southern end of this peak; each sampling site was approximately 10 m in diameter.

The vegetation at the study site was cold desert perennial scrub and was dominated by *Agropyron desertorum* (C₃), *Artemisia tridentata* (C₄), *Atriplex confertifolia* (C₄), *Bromus tectorum* (C₃), *Elymus elymoides* (C₃), *Chrysothamnus viscidiflorus* (C₃), *Eurotia lanata* (C₃), *Gutierrezia sarothrae* (C₃), *Juniperus osteosperma* (C₃), *Munroa squarrosa* (C₃), *Oryzopsis hymenoides* (C₃), and *Salsola iberica* (C₄). All sites sampled along this transect consisted of undisturbed vegetation, except for the site that was nearest the active vents and had the highest CO₂ concentrations. This site was marked by disturbances made in the past from attempts to bulldoze the area and extinguish the burning coal.

Atmospheric CO₂ Measurements

Atmospheric CO₂ concentrations were measured with an infrared gas analyzer (IRGA; LI-6200, Licor, Lincoln NE, USA). At each site, CO₂ was measured every 1 s for 60 s and averaged to derive a single sample value. This sampling was repeated six to nine times per site to get an overall estimate of the mean CO₂ concentration and variability at a site. During the entire sampling period, the wind was moderate (1–3 m s⁻¹) from the south, which is typical for summer in this region (Ashcroft et al., 1992).

Carbon Isotope Composition of Dry Leaf Matter

Carbon isotope discrimination was determined on bulked samples that consisted of at least five sunlit, exposed leaves on each of five plants per species at a site. The material from individual plants was oven-dried, combined to form a single composite sample, and ground to a fine powder. A 2-mg subsample of the powder was combusted and analyzed by an elemental analyzer coupled to an isotope ratio mass spectrometer (C.F. Kitty, delta S, Finnigan-MAT, Bremen, Germany). The overall precision of sampling, combustion, and analysis was ± 0.1‰. The carbon isotope ratio was calculated in parts per mil, using "delta" notation as:

$$\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000\text{‰} \quad (3)$$

where R is the molar ¹³C/¹²C ratio of either the sample or the standard (PDB).

To better describe ecophysiological effects on the carbon isotope content of C₃ plants, we calculated the carbon isotope discrimination (Δ) of leaf material from its measured δ¹³C value, as described by (Farquhar et al., 1989):

$$\Delta = (\delta^{13}\text{C}_{\text{air}} - \delta^{13}\text{C}_{\text{plant}}) / (1 + \delta^{13}\text{C}_{\text{plant}}) \quad (4)$$

where δ¹³C_{plant} was derived from the δ¹³C measurements as described above and δ¹³C_{air} was derived as described below. In this case, discrimination is preferable to δ¹³C because it expresses the effects of biological processes, independent of the δ¹³C value of the source air (Farquhar et al., 1989).

The δ¹³C_{air} value was not directly measured, but instead was calculated in the manner described by Marino and McElroy (1991), who capitalized on the near constant photosynthetic fractionation by C₃ plants (all terms influencing δ¹³C_{plant} except δ¹³C_{air} in Equation 1). They measured δ¹³C_{plant} and assumed a constant photosynthetic fractionation, allowing them to calculate δ¹³C_{air} as a residual. We calculated the baseline C₄ discrimination value (δ¹³C_{plant})



measured in a "clean" site 10 km upwind from the burning coal seam. The $\delta^{13}\text{C}_p$ for each site was then calculated by subtracting the C_p discrimination value from the observed $\delta^{13}\text{C}_{\text{plant}}$ values of the C_p plants within these sites. The atmospheric CO_2 concentrations were then calculated from a linear mixing model using the $\delta^{13}\text{C}_p$ based on C_p plants, and the bulk atmospheric air based on observations at the control site.

Results and Discussion

We measured distinct gradients in ambient CO_2 concentration around the burning coal vents; atmospheric CO_2 concentrations decreased with distance from the most active vents. Immediately adjacent to the largest vents, we were unable to measure CO_2 concentrations, which were higher than the 2,000 ppm upper limit of our IRGA. However, there was no active vegetation in the area immediately adjacent to these vents; the closest vegetation to the primary vents was approximately 50 m distant, where the atmospheric CO_2 concentration averaged 895 ppm. There was substantial variation about this mean CO_2 concentration associated with shifting wind. Atmospheric CO_2 near this vegetation varied ± 134 ppm (standard error). At undisturbed sites 100 m upwind, the atmospheric CO_2 concentrations were lower than 420 ppm and exhibited substantially less variability. CO_2 concentrations 500 m from the most active vents averaged 7 ppm above the control site 10 km to the north, where atmospheric CO_2 concentration was 352.1 ± 0.6 ppm, which was very close to the global average atmospheric CO_2 of 354 ppm at that time (Keeling and Whorf, 1994). Overall, there was a strong positive correlation

between the mean CO_2 concentration at a site and the total range of CO_2 concentrations measured with the IRGA ($r = 0.99$, $n = 7$, $P < 0.01$).

Carbon isotope ratios of the C_p vegetation varied substantially in association with changes in atmospheric CO_2 concentration (Figure 1). Vegetation closer to the active vents was more depleted in ^{13}C , as was the CO_2 of the vent efflux (Gleason and Kyser, 1984). *Atriplex confertifolia* and *Salsola iberica* were the most common C_p species along the gradient and exhibited $\delta^{13}\text{C}$ values ranging from -20.7 to -12.6‰. *Munroa squarrosa* occurred at three of the microsites sampled and its isotopic composition varied from -15.2 to -13.7‰ in a manner consistent with the isotopic changes in the other two C_p species.

Because the carbon isotope ratio of leaves of C_p plants reflects ambient CO_2 levels metabolically weighted over the life of that leaf, the range of $\delta^{13}\text{C}$ values we observed in the C_p species suggests that these plants could provide a means of estimating long-term integrated CO_2 concentrations along the elevated CO_2

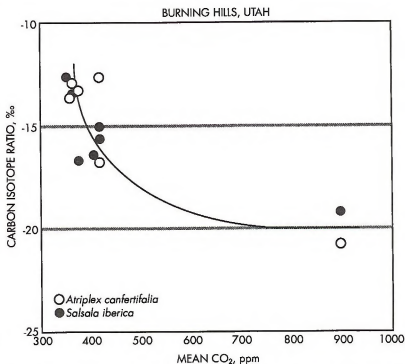


Figure 1. The carbon isotope ratios of leaves of two C_p species at different sites near a burning coal vent as a function of atmospheric CO_2 as measured with an IRGA.



gradient. Indeed, the calculated CO_2 concentration compared favorably with IRGA observations at the different sites ($r = 0.797$, $P < 0.05$, Figure 2). At slightly elevated

factors that relate to plant CO_2 uptake and water loss (i.e., gas exchange rates), we expected these values to be most impacted by the burning vents. *Gutierrezia sarothrae* was

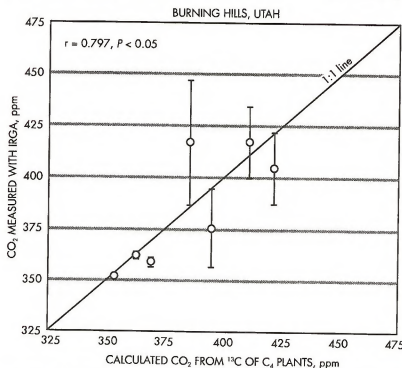


Figure 2. The correlation between the measured atmospheric CO_2 (IRGA measurements) and the atmospheric CO_2 concentration calculated from the ^{13}C of C_4 plants at this site. Vertical lines indicate the 95% confidence interval surrounding the IRGA CO_2 measurements.

atmospheric CO_2 concentrations (365–425 ppm), which occurred at distances of 200 m to 300 m from the vents, there was very close agreement between predicted and actual CO_2 concentrations. However, at the highest atmospheric concentrations there was some discrepancy between the instantaneous IRGA measurements and the longer term integrated isotopic values, which is most likely explained by physiological theory that predicts C_4 plants will exhibit increased C_3 -like isotope ratios under CO_2 concentrations in excess of 1,500 ppm (Vogel, 1993).

Overall, the CO_2 concentrations at the locations near the burning coal seams were significantly elevated above natural conditions, suggesting that sites in this area might be useful locations for evaluating plant performance under elevated CO_2 . Because the carbon isotopic composition of C_4 plants integrates several

the only C_3 species distributed continuously along the CO_2 gradient we studied. Leaf carbon isotope discrimination values (Δ) decreased from 20.2 to 13.5‰ as atmospheric CO_2 concentrations increased from 352 to 422 ppm (Figure 3). The changes in the calculated leaf Δ values were equivalent to a decrease in the c/c_s ratio from 0.7 to 0.4 (Equation 2). This change in the c/c_s ratio was large enough that it should reflect a significant impact on plant gas exchange rates (Farquhar et al., 1989). This impact may be the result of CO_2 -induced changes in several metabolic and structural characteristics of the affected leaves, such as increased stomatal closure, changes in the stomatal limitations to photosynthesis, and in chloroplast demand for

CO_2 (Ehleringer, 1993), and over longer time periods, in stomatal size and density (Beerling and Chaloner, 1992).

At the community level, carbon isotope discrimination values decreased as atmospheric CO_2 levels increased. For plants still active at the August sampling period (*Agropyron*, *Coleogyne*, *Ephedra*, *Gutierrezia*, and *Oryzopsis*), leaf Δ values were significantly correlated with the CO_2 concentrations at the respective sites. The correlation was highly significant ($r = 0.76$, $P < 0.02$, $n = 18$) despite large differences in the individual values among species.

At the whole-plant level, the calculated decrease in c/c_s ratios would result in a doubling of water-use efficiency in plants along this gradient (Ehleringer et al., 1992). Increased plant water-use efficiency, the ratio

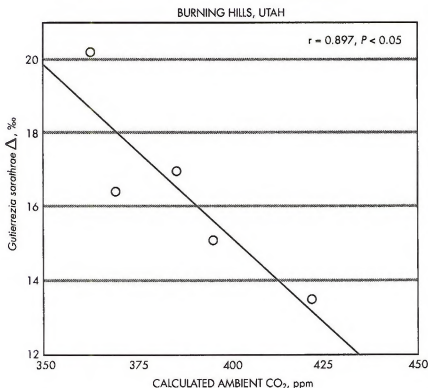


Figure 3. The relationship between carbon isotope discrimination in *Gutierrezia sarothrae* (a C₃ plant) and atmospheric CO₂ as estimated by the ¹³C content of surrounding C₄ species at the site.

of carbon gain to water loss, may result in improved soil and plant water status, and alleviate the water limitations to productivity that exist under normal CO₂ levels (Field et al., 1996). Since soil moisture is the primary climatic factor limiting productivity in aridland ecosystems, any mechanism that alters system-level water availability by decreasing the rate of soil moisture extraction might provide a growth advantage to plants, most likely perennials, capable of utilizing the remaining moisture later in the season. While we have no data available yet showing that soil moisture is retained longer in this particular aridland ecosystem, Field et al. (1992) have suggested that CO₂ should result in greater soil moisture retention at depths not subject to surface evaporation and thus possibly extend productivity to later periods in the drought. In the GSENM ecosystem, shrubs and trees might be favored over native grasses in this scenario. Additionally, in other mixed C₃-C₄ communities, other limiting factors such as N availability have had greater impacts on CO₂-fertilized C₄ plants, thus favoring C₄ plants (Owensby et

al., 1996). Exotic C₄ weeds such as *Salsola* and *Halogeton*, which have invaded much of GSENM, might be favored over native species under elevated CO₂.

The burning coal vents in the GSENM have the potential to serve as a vehicle for examining elevated CO₂ effects on aridland vegetation. Aridland ecosystems are predicted to be among the more sensitive to elevated CO₂ concentrations if stomatal closure results in a reduced rate of soil moisture loss (Neilson, 1995; Field et al., 1997). That is, growing season length is expected to increase under elevated CO₂, because early season water conservation allows for extended periods of water use late in the growing season. Several factors make the vents in the Burning Hills of the GSENM particularly well-suited for exploring these potential impacts. The vents have several advantages over artificially elevated CO₂ experiments, such as the FACE experiments:

- FACE experiments only achieve a single, elevated CO₂ concentration, whereas the burning coal vents offer a gradient of CO₂ levels.
- FACE experiments are recent in time, and only a handful have been active for more than a few growing seasons (Miglietta et al., 1993); it will be years before effects on long-lived perennials, and on long-term ecosystem processes and community changes, will be apparent. These experiments are expensive, and are rarely replicated within ecosystem types. The vents of the GSENM offer replication in both time and space: there are many of them and they have been burning for various lengths of time, some for potentially



thousands of years (H.H. Doelling, pers. comm.).

- The ability of the GSENM to protect these ecologically important areas from further disturbance makes them more desirable for long-term research than other burning coal seams in southern Utah that are not on protected lands.

Burning coals vents are somewhat analogous to the elevated CO₂ springs described by Miglietta et al. (1993). These geothermal sources occur throughout the Mediterranean-climate landscape in central Italy and provide a resource for evaluating plant acclimation and adaptation to elevated atmospheric CO₂ conditions. In both systems, atmospheric turbulence will result in fluctuation in the absolute CO₂. While the extent to which stomata can respond to high-frequency changes in CO₂ concentration is unknown, carbon isotope ratios of C₄ plants will provide an estimate of the long-term, assimilation-weighted value of the atmospheric CO₂ concentration.

Several possible limitations to burning coal vents as natural experimental systems should also be considered. For instance, there could be complications arising from oxidation of sulfur within the coal seams if baseline sulfur levels were high enough to cause SO₂-induced stomatal closure (Taylor and Pitelka, 1991). We did not directly measure atmospheric SO₂ levels, but from observations in the area, there were no indications of sulfur deposition near the soil surface. The coal seams contained less than 0.8 percent sulfur and are known to be water-saturated (Doelling and Graham, 1972). It is possible that SO₂ formed during combustion processes was partly dissolved in deep soil water before these gases could reach the surface, thereby minimizing any possible SO₂ effects. The Burning Hills of the GSENM are distinct from similar burning coal seams in other parts of the world (e.g., arctic Smoking Hills as described by Havas and Hutchinson, 1983) in that they are substantially lower in sulfur content. While it is not possible to keep SO₂ effects from confounding data

interpretation, the available evidence suggested that this possible impact would be minimal. Additionally, these burning coal vents are characterized by an incomplete combustion, resulting in a release of saturated hydrocarbons in addition to CO₂. Using measured vent concentrations from Gleason and Kyser (1984), we calculated that methane and saturated hydrocarbon concentrations at our sampled sites were approximately 5 ppm. While we are unaware of any studies indicating that methane and other hydrocarbons at these concentrations have an adverse effect on stomatal activity, direct experimentation is necessary to test this possibility.

As a management and scientific tool, the burning coal vents of the GSENM offer an unusual opportunity to meld both aridland grazing and natural scientific interest in trying to understand how southern Utah ecosystems will respond to the high atmospheric CO₂ concentrations that are anticipated to occur during the next century. Which plants will respond positively to elevated CO₂? Which plants will respond negatively? How much will elevated CO₂ extend the period of plant productivity? These are important research questions that both land managers and scientists alike need to have answered. The burning coal vents are an opportunity to bring these two interests together to address questions of common interest.

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A Plan to Assess Native and Exotic Plant Diversity and Cryptobiotic Crusts in the Grand Staircase-Escalante National Monument

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ABSTRACT

■ Land use practices such as grazing, recreation, and mining, can have direct and indirect effects on plant diversity in the Grand Staircase-Escalante National Monument (GSENM). Proper care and management of the botanical resources in the Monument will require an unbiased landscape-scale assessment of native and exotic plant diversity, including cryptobiotic crusts, a science-based long-term monitoring program for vegetation and soils, and geographic information system-based ecological models to aid decisionmaking. Understanding of landscape-scale botanical resources has been hampered by single-scale or poor multiscale sampling methods, large minimum mapping units (i.e., coarse resolution vegetation type maps), limited and subjectively selected field observations, and poor mathematical and ecological models. Our plan overcomes these obstacles with improved multiscale sampling techniques, smaller minimum mapping units (based on landscape scale vegetation patterns), an unbiased sampling design based on double sampling, improved mathematical models including species-area curves corrected for habitat heterogeneity, and geographic information system-based ecological models. Our systematic surveys will assist the Monument staff in: 1) identifying hot spots of native plant diversity and rare/unique habitats; 2) determining areas where cryptobiotic crusts and plant communities are particularly sensitive to disturbance; 3) detecting the loss of native plant diversity caused by exotic plant species or land use practices; and 4) developing a science-based, long-term monitoring plan for vegetation, cryptobiotic crusts, and soil resources.

important ecological values, including the high number of endemic species in "the heart of perhaps the richest floristic region in the Intermountain West." It recognizes the "abundance of unique, isolated communities...which have provided refugia for many ancient plant species for millennia." Furthermore, the Presidential Proclamation specifically recognizes the "extraordinary opportunity to study plant speciation and community dynamics" in the Monument.

The Presidential Proclamation establishing Grand Staircase-Escalante National Monument identifies the Monument's



Throughout the 691,057-ha (1.7-M-acre) Monument, there are botanical and soil resources of interest and concern. With elevation ranging from 1372 m (4,500 ft) to 2530 m (8,300 ft), vegetation life zones range from low desert shrub, steppe, sage, and pinyon-juniper woodlands to Ponderosa pine supporting a diverse flora and fauna. The flora is composed of species from the Mojave and Sonoran Deserts and the Great Basin. Relict grasslands and riparian zones create opportunities to understand and protect genetic diversity. As part of the Colorado Plateau floristic division in the state of Utah, the area is home to 50 percent of the rare plants and 84 percent of the entire flora of Utah (Shultz, 1998). Earlier botanical surveys of the Kaiparowits Basin resulted in a checklist of 851 vascular plants (Welsh and Atwood, 1998).

Eleven plant species are found nowhere else on Earth. The high degree of endemism of vascular plants is exemplified by the hanging gardens (Fowler et al., 1995; May, 1998). Hanging gardens are rare, geomorphological enclaves of mesic habitats interspersed in vast areas of desert. They support unique species of plants including Maidenhair ferns, orchids, sedges, and flowers that cling to the steep Navaho Sandstone. These resources may be particularly vulnerable to human-caused disturbance (May, 1998).

Cryptobiotic (or microbiotic) soil crusts are a filamentous web of blue-green algae, lichens, green algae, and fungi. They play a critical role in maintaining the sustainability of desert ecosystems by stabilizing soils, preventing accelerated erosion, protecting soil biota, and facilitating nutrient and water cycling for plant productivity (Belnap and Harper, 1995; Belnap and Gillette, 1997). However, these fragile organisms are often disrupted by trampling by livestock and people and by off-road vehicle use (Belnap, 1995, 1998). Disturbance to crusts can lead to accelerated soil erosion, slowed decomposition of soil organic matter, and, perhaps, lower productivity or diversity of vascular plants (Belnap, 1996). Ecosystems within the Monument are especially vulnerable to disturbance since it is estimated

to take several hundred years for crusts to recover from compaction.

Strategic Management Issues

Identifying Hotspots of Native Plant Diversity and Rare/Unique Habitats

Biological conservation efforts are increasingly moving toward an ecosystem and landscape approach, recognizing the prohibitive cost and difficulty of a species-by-species approach (Agee and Johnson, 1988; Noss, 1983; LaRoe, 1993). A key ingredient of our approach is a careful analysis of hotspots of plant diversity and rare/unique habitats to identify critical habitats (keystone ecosystems). Examples of keystone ecosystems include those associated with rare geologic features (e.g., rock outcrops, mineral licks) and distinctive (or transient) vegetation communities (early successional seres, rare plant associations). Although these ecosystems are small in total area, they often are used heavily by large ungulates as grazing areas and migratory corridors (McNaughton, 1993). In the Monument, riparian zones and small wetlands are expected to be hotspots of biodiversity. A proactive approach to resource management requires a composite picture of the spatial arrangement and configuration of keystone areas and their linkages in landscapes.

Determining Areas Where Cryptobiotic Crusts and Plant Communities Are Particularly Sensitive to Disturbance

Our understanding of the role of the Monument's cryptobiotic crusts in maintaining and stabilizing soils and protecting native plant diversity can be greatly improved with systematic surveys combined with controlled experiments (Belnap and Harper, 1995; Belnap and Gillette, 1997). Cryptobiotic crusts are more prevalent in some areas of the



Monument than in other areas, while some areas receive more trampling by livestock and people, off-road vehicle use, or other disturbances. It is likely that some types of crusts or specific habitats may be more resistant or resilient to disturbance than others. Our systematic surveys will identify the distribution of sensitive species and habitats in the Monument.

Detecting the Loss of Native Plant Diversity Caused by Exotic Plant Species

Native plant diversity in the western U.S. has been greatly affected by development, recreation, agriculture, and livestock grazing. Recent studies are showing that exotic plant species are invading hotspots of native plant diversity such as tallgrass prairie, wet meadows, and aspen communities in the Rockies, and riparian zones throughout the West. Some species of weeds are toxic to livestock and wildlife, but their patchy distribution makes them difficult to detect and control. Others are spreading readily and may become dominant. Cheatgrass (*Bromus tectorum*), for example, establishes after fire and is likely replacing native species locally and further increasing fuel loads and fire return intervals in a positive feedback cycle. Preserving native plant diversity will become increasingly difficult as exotic plants continue to invade. Only by knowing the locations of exotics and the structure of the landscape-scale vegetation and soils matrix can predictions be made about invasions and successful management actions be taken.

Developing a Science-Based Long-Term Monitoring Plan for Vegetation and Soil Resources

It is critical to identify and locate past and current land use practices, quantify impacts to vegetation and soils, and plan future developments and land uses to minimize impacts. Locating suitable "control" sites is often difficult, but not impossible. The impacts of livestock grazing, for example, will be assessed as a

"gradient analysis study" along grazing intensities from frequent/heavily used sites to infrequently used sites (e.g., No-Mans Mesa). Mineral exploration, recreation, and grazed sites will be evaluated with a system of three-plot replicates: one in the disturbed site, one adjacent, and one randomly located on the landscape in the same vegetation type. This approach is needed to isolate land use impacts from background levels of spatial variability and to accurately quantify the status and trends of plant diversity at local and regional scales (Stohlgren et al., 1997a,b,c; Stohlgren, et al., 1998a,b). A subset of plots in each vegetation type will be systematically selected for long-term monitoring (Stohlgren, 1998a,b,c).

Our objectives are to work closely with the Monument staff to produce: 1) detailed baseline data on native and exotic plant species, cryptobiotic crust communities, rare/unique habitats, and soil characteristics; 2) geographic information system (GIS)-based spatial analyses of the patterns of plant diversity, keystone ecosystems and hotspots of diversity, and rare/unique habitats; 3) a working herbarium collection; and 4) the development of a long-term monitoring program to evaluate the status and trends of botanical resources.

Proposed Methods

Unbiased Site Selection

Sample sites are selected in an unbiased manner using remotely sensed information and a stratified random sampling design. Land use units (by grazing regime, past use, etc.) and vegetation types are stratified to include homogeneous plant communities (typically recognized in most vegetation mapping efforts) and heterogeneous communities of special interest (e.g., ecotones and ecoclines, wetlands, riparian zones, relict plant communities) (Stohlgren et al., 1997a,b).

The size of the minimum mapping unit will be selected to accommodate a particular habitat such as relict plant communities. We



expect a minimum mapping unit of 0.02 - 0.05 ha so that small patches of rare plant communities would be included in the stratification. Using the Monument's coarse-scale vegetation map and knowledge of rare habitat types, four or five ground truth plots will be randomly located in each vegetation type using a GIS. We will locate the points in the field with the aid of aerial photographs, other maps, a compass, and a handheld Global Positioning System (GPS). For each field site, we will calculate slope, aspect, and elevation (using digital elevation models and our GPS information).

Multiscale Vegetation Sampling

At each ground truth sampling point, a modified-Whittaker nested vegetation sampling plot will be established (Stohlgren et al., 1995). The modified-Whittaker plot is 20 m x 50 m, with a 5-m x 20-m (100-m²) subplot in plot center, two 2-m x 5-m (10-m²) subplots in opposite corners, six 0.5-m x 2-m (1-m²) subplots arranged systematically inside and adjacent to the plot perimeter, and four 1-m² subplots arranged systematically outside and adjacent to the 100-m² subplot. In the ten 1-m² subplots, we will record the foliar cover and height by species, and the cover of bare ground, cryptobiotic crust (moss, lichen, cyanobacteria), rock, litter, duff, water, and dung. Designing the appropriate crust sampling methods will be an iterative process. We suspect that a combination of 0.25-m² frames and point-hit frames will be used. Cumulative species (additional species found in the subplot or plot) will be recorded successively in the ten 1-m² subplots, the two 10-m² subplots, the 100-m² subplot, and the remaining unsampled areas of the 20-m x 50-m plot. For small vegetation communities, the dimensions of all the subplots and plots can be reduced proportionately. We will establish three to five modified-Whittaker plots in each vegetation type, stratified further by land use. The unique-to-vegetation type species, which are likely to be the species of most conservation interest, also will be noted. We will use a GPS to document the locations of the plots and

incorporate the data directly into both the Monument staff's GIS and our GIS.

Determination of Species-Area and Species-Habitat Relationships

Cumulative species data from the 1-m², 10-m², and 100-m² subplots from each 1000-m² plot will be fit to linear regressions of cumulative species-area curves, species-log (area) curves, and log (species)-log (area) curves. To validate the selected model, the estimated total number of species in each 1000-m² plot based on the 1-m², 10-m², and 100-m² data can be compared to the observed number of species recorded in each plot. The regression model with the least difference between observed and expected values should be used. Species-area curves based on replicate plots must be corrected for within-vegetation-type heterogeneity (Stohlgren et al., 1997a,b).

We will estimate the number of native and exotic plant species that occur on a landscape by estimating the total number of species found in the two vegetation types with the greatest numbers of unique species using the species-area curve corrected with Jaccard's coefficient (*J*) from the actual species lists and the area of that type calculated from the GIS (Stohlgren et al., 1997a,b). Since the species lists of the two types overlap by some percentage (*J*), the total number of species is determined by summing the two types and then subtracting *J* percent of the estimated number of species in both types. The estimated number of species is calculated for the vegetation type with the next greatest number of unique species (again using the species-area curve corrected for species overlap). This type is added to the first two vegetation types and then the expected overlap for those two types is subtracted from the estimated number of species of the composited types. These steps are repeated until all vegetation types are combined. Species affinities to particular habitats will be assessed by evaluating species overlap among communities, and particular affinities to specific habitats.



Simultaneous Surveys of Crusts and Selected Soil Characteristics

Systematic surveys of soil crusts, along with vegetation sampling, will greatly improve our understanding of the relationships among vascular plant diversity, cryptobiotic crusts, and soil characteristics. Surveys of crusts and soil characteristics in different habitat types under different land-use regimes will provide quantitative information for species distribution and rare habitat models to guide resource management.

Twenty soil samples will be taken throughout each modified-Whittaker plot and pooled into one plastic bag. For each sample, the surface litter, if present, will be removed, and the top 15 cm of soil will be sampled (when possible). Samples will be air-dried for 48 hours, sieved with a standard #10 (2-mm pore size) sieve, ground in a standard three ball grinder, and then oven-dried at 55 °C for 24 hours. Samples will be analyzed for K, Mg, Ca, Na, (contracted soils laboratory), and percent total carbon and percent total nitrogen using a LECO-1000 CHN Analyzer (following the methods of Carter, 1993), and for particle size based on the standard hydrometer method (Gee and Bauder, 1986). Soils characteristics will be correlated with data on native and exotic plant species richness, foliar and micro-biotic crust cover, and species height in the various vegetation and land use units (Stohlgren et al., 1998a).

Long-Term Monitoring, Information Management, and Predictive Models

A subset of plots in each vegetation type will be systematically selected for long-term monitoring (Stohlgren, 1998a,b,c). Criteria for selection will include: 1) representativeness based on similarity indices, foliar cover, or frequency, and soil characteristics; and 2) specific management needs. Because these sites were initially selected in an unbiased manner, they create a statistically powerful means to evaluate spatial and temporal variation

and the status and trends of botanical resources. Two alternate plot corners will be staked with copper-topped survey stakes and engraved. GPS notes and field location maps will assure relocation. Developing long-term monitoring plans must be an iterative process. Sample variances must be monitored and sample size adjusted in some cases, such as where temporal or spatial variation is very high. Where temporal variation is low (i.e., where there is little change from year to year), sampling frequencies can be decreased.

Proper information management is the backbone of ecological studies. It requires: 1) clearly articulated goals and objectives; 2) a commitment to preserving the integrity, longevity, and accessibility of the data for future unforeseen uses by you and others; 3) a detailed vision of how the data will be gathered, stored, summarized, statistically analyzed, displayed, and archived; and 4) an understanding of the quality and limitations of the data (Stohlgren, 1998c). It requires the timely transfer of information to and from scientists, resource managers, and the public. Our use of palmtop computers for data entry, customized analysis software, and experience with GIS technology and managing landscape-scale survey data ensure a strong information management process.

The real strength of unbiased, multiscale vegetation and soil surveys lies in developing and validating predictive models. Predictive models are an important step in avoiding conflicts with user-advocacy groups or the degradation of biotic resources and populations of special concern. The models also can be powerful tools in planning, teaching and training, and public outreach. The series of geo-referenced long-term study plots will be used to validate model predictions in the coming years and decades. New "co-kriging" spatial analysis models will be used to develop probable species distribution maps for species of special concern and maps of hotspots of diversity or distinctive plant communities. GIS-based models will evaluate species-environment relationships (i.e., relationships of botanical and soil resources to elevation, slope, and aspect).



Biological diversity is a complex outcome of the environment, population and metapopulation processes, competition, predation, succession, dispersal, and colonization. Thus, modeling biodiversity mechanistically is a formidable task. Different modeling approaches attack different aspects of the problem in different ways. These include empirical models of diversity as functions of landscape variables, models of plant succession and competition, metapopulation models, and species-area curves.

Benefits to Management

Conservation and wise stewardship of public lands require high-quality, statistically-sound scientific information at appropriate spatial scales and resolutions. Also, as U.S. Department of the Interior land units become more insular, management alternatives are constrained, and new, creative solutions are needed to meet environmental challenges. It has become increasingly more obvious that determining the status and trends of natural resources cannot be viewed from within a single land management unit. Coordinated landscape planning is essential, and detailed, unbiased data must guide the planning and management efforts.

Typical vegetation mapping projects on Federal lands use fairly large "minimum mapping units" of 2 ha to 5 ha, and sometimes larger (e.g., GAP Analysis; Scott et al., 1993), and thus include only information on a few dominant overstory vegetation types. A minimum mapping unit is the smallest area delineated on a remotely sensed image or vegetation map. Such large minimum mapping units miss small habitat patches, fail to distinguish between most seral stages, and generally do not detect gradual ecotones and other important landscape features (e.g., small wetlands and riparian zones). In contrast, our sampling approach specifically recognizes rare and potentially important small habitats, and our multiscale sampling designs provide detailed data on distributions of native and

exotic plant species, effects of land use on plant diversity, and location of rare species and habitats.

Commonly used vegetation sampling techniques such as Parker transects (Parker, 1951), Daubenmire transects (Daubenmire, 1959), and other transect and quadrat methods significantly underestimated the total species richness, the number of native and exotic species, and the number of species with less than 1 percent cover in grassland vegetation types (Stohlgren et al., 1998a). Our multiscale modified-Whittaker method, which includes an exhaustive search for plant species in a 20-m x 50-m area, captures twice as many plant species than replicated transect methods. The detection and measurement of exotic plants, including noxious weeds, was greatly enhanced by using a multiscale sampling design. Even replicated transect methods were less effective than multiscale techniques due to small sample areas, spatial autocorrelation bias, and missed rare species and habitats. Multiscale sampling methods may better monitor the spread of exotic species and evaluate range conditions and trends at local, regional, and national scales compared to the commonly used transect methods (Stohlgren et al., 1998a).

Our sampling approach has many other benefits. We have replaced field data sheets with palmtop computers to provide resource managers immediate access to raw and summarized data. We are developing powerful spatial analysis techniques—co-kriging models—which combine vegetation and environmental data to produce accurate, GIS-based predictive models and "maps with error bars" so managers are provided with information on the precision, accuracy, and level of uncertainty of resource maps. Lastly, our landscape-scale sampling approach is proven to be cost-efficient, information rich, and well-accepted by the scientific community (Stohlgren et al., 1995; 1997a,b,c; 1998a,b).

The Monument staff will be responsible for extensive GIS support, botanical expertise, and administrative and logistical support. The



local GIS expertise is needed to obtain and interpret aerial photography, develop the high resolution vegetation map, and merge the physical, cultural, and biological databases at the Monument. Local botanical expertise is needed to assist and guide our field crews on occasion, and to help establish and maintain the working herbarium. Administrative support is needed to obtain and transfer funds, brief field crews, issue collection permits, and provide logistical support (some helicopter transportation, some lodging or campground use as needed).

In the first year of the project, we will:

- 1) establish at least 30 modified-Whittaker multiscale vegetation/crust/soil sampling plots in areas selected by the Monument staff;
- 2) continue developing components for a long-term inventory and monitoring plan for vegetation, crusts, and soils 3) assist in developing a working herbarium at the Monument; and
- 4) create a color brochure and slide presentation of the "Rapid Assessment of Native and Exotic Plant Diversity in the Grand Staircase-Escalante National Monument" for outreach purposes.

Long-term expected products include:

- 1) detailed baseline information and maps of hotspots of native plant diversity and areas with distinctive floras (relict plant assemblages);
- 2) detailed baseline information and maps of exotic plant species distributions and noxious weeds; and 3) predictive spatial models and maps of potential hotspots of native plant diversity, probable locations of rare habitats and relict species assemblages, and potential areas of future weed invasions. Expected publications include the "Effects of Grazing on Native and Exotic Vascular Plant Species and Soils," "Preserving Native Plant Diversity and Soils," "New Spatial Analysis Models for Conservation Biology," "Patterns of Microbiotic Crusts in Landscapes of Grand Staircase-Escalante National Monument, Utah," "Vascular and Nonvascular Plant Ecology in Grand Staircase-Escalante National Monument, Utah," and more.

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Ecological Characterization of the Canyon Country Region: A Basis for Sustainable Land Management

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ABSTRACT

■ The canyon country of southeastern Utah and adjacent portions of Colorado is a region of about 5 million hectares that constitutes a large portion of the northern Colorado Plateau. The rapid growth of recreation and commercial tourism, alongside traditional land uses, has put added stresses on the canyon country's sensitive soil and biotic resources. The challenge for public land managers is to sustain the health of the region's ecosystems while still meeting the needs and desires of the people who use the land—a process we term *sustainable land management*. Key to this process is the acquisition of ecological information on the composition and functioning of the land.

An ecological characterization study to acquire such information has been designed by the Canyon Country Science Committee, a group of agency and organizational scientists based in the region. This multiyear study comprises a stepwise series of products that are generated over a range of geographic scales. Initial phases of the project involve the definition of biophysical environments and modeling of potential natural vegetation within a circa 230,000-hectare pilot area in San Juan County known as the Canyon Country Ecosystem Research Site. Subsequent phases of the study involve definition of landscape units, inference of historic ranges of variability, and predictive modeling of vegetation changes and landscape dynamics. Ultimately, this characterization study represents a scientific foundation to be used by decisionmakers to address land-use planning and management issues.

This study may be highly useful for the Grand Staircase-Escalante National Monument in that the characterization results may be extrapolated to portions of the Monument that are similar to the canyon country. Parts of the Monument that are dissimilar can be characterized using the same methodology as the canyon country study. Eventually, characterization work in the canyon country and the Monument can be expanded to cover the Colorado Plateau as a whole. Finally, the canyon country study will involve an interactive network of agency and academic scientists whose long-term interests will likely be sufficiently broad in scope to include part or all of the Monument.

The canyon country of southeastern Utah and adjacent portions of Colorado is a region of about 5 million hectares that constitutes a sizable portion of the northern Colorado Plateau. As defined by this paper, the canyon country is roughly bounded on the north by the Tavaputs Plateaus; on the west by the Wasatch Plateau and Waterpocket Fold; on the south by the San Juan River; and on the east by Comb Ridge, the Uncompahgre Plateau, and other natural features (Figure 1).

In recent years, the canyon country region has been experiencing an unprecedented "boom" in land-use demands. This has been fueled largely by explosive growth in recreation and

tourism, typified by the dramatic increases seen during the past 7-10 years in the area of Moab, Utah. Also escalating are residential development in remote areas and commercial

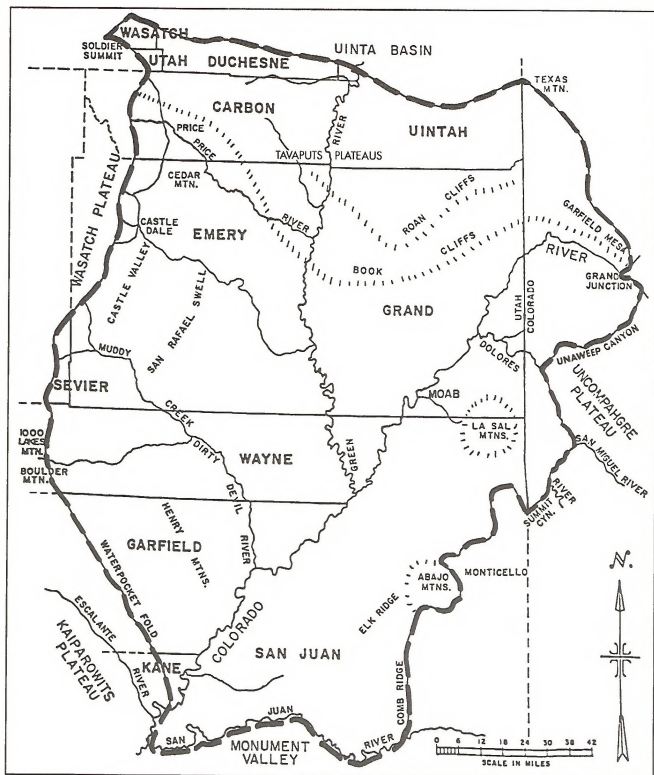


Figure 1. The canyon country of southeastern Utah and adjacent portions of Colorado is a region of about 5 million hectares that constitutes a sizable portion of the northern Colorado Plateau. As defined by this paper, the canyon country is roughly bounded on the north by the Tavaputs Plateaus; on the west by the Wasatch Plateau and Waterpocket Fold; on the south by the San Juan River; and on the east by Comb Ridge, the Uncompahgre Plateau, and other natural features.



ventures such as filming, large recreational events, and guiding services. These expanding uses occur alongside and often conflict with traditional activities such as grazing and mineral development. Cumulative impacts from all of these land uses are contributing to rapid deterioration of sensitive soil and biological resources, especially in areas where such uses are concentrated.

Most of the canyon country region is in Federal, State, or Indian ownership. Attempting to meet user demands often causes conflicts among the managers of these varied lands, and among segments of the public. Many communities have become highly polarized over land use issues, and many proposed management actions have been subject to time-consuming, costly protests.

To date, these land use conflicts have been significant primarily at a regional scale. That is, the canyon country has not encountered national-level, politically contentious, land use issues of the magnitude that have stymied management in the Yellowstone area and the Pacific Northwest. However, the potential exists for several simmering issues to become very contentious if they are not effectively addressed. Examples of such issues include endangered species designations and introductions, large-scale Federal land classification changes, water depletions, salinity, and range reform.

The canyon country region is thus an ideal location to implement a test case for land management that gets out ahead of land use issues so that they do not degenerate into "environmental train wrecks." Further, lessons learned from such a prototype effort in the canyon country should be exportable and thus highly beneficial to adjacent portions of the Colorado Plateau, such as the Grand Staircase-Escalante National Monument ("Monument").

Sustainable Land Management

At the heart of this subject, land and resource managers of the canyon country must wrestle

with a dilemma that is becoming ever more acute: How do we manage the land to derive multiple, often competing values now, and also *sustain the ability* of the land to continue providing such values for ourselves as well as for our descendants?

Historically, human settlement of the canyon country was supported by use of the region's natural resources. This custom endures today, as various uses of the land provide a variety of values for society's benefit. However, if we "use up" renewable natural resources faster than they can be restored, then we have left future generations with a poorer quality world than we now enjoy. Congress addressed this concern in the Multiple Use-Sustained Yield Act of 1960. If our greatest legacy—our descendants—is to inherit the same opportunities for the variety of land uses that we now have, then we must ensure that the concept of "sustained yield" is realized.

These ideas are confirmed in the laws and regulations of two major land management agencies in the region: the Bureau of Land Management and the USDA Forest Service. Though the National Park Service does not have the same type of mandate for multiple uses, that agency is still required to provide for the enjoyment of people while passing on the land unimpaired to future generations. Even private businesses and people whose economic livelihoods depend on the land know that they cannot degrade or deplete their resource base if they are to prosper.

The aim, therefore, is to achieve land management that: 1) maintains the basic health and sustainability of ecosystems, and 2) serves the sometimes-competing needs of people who depend upon such ecosystems for commodity or noncommodity values. This process has been termed "Ecosystem Management." It can also be thought of as *sustainable land management*—management that maintains both the basic health and integrity of the land and the production of values to meet society's needs. One way of looking at this process is shown in Figure 2. The land ecology circle represents the "natural" composition, functioning, and



Figure 2. Sustainable land management is a set of possible land use allocations that meets human desires and needs, and that the land is able to sustain over the long-term.

term. This is the model that will best enable us to pass on land use opportunities to future generations.

Strategies for gathering and analyzing the information represented by the two circles in Figure 2 have begun to be developed by a group known as the Canyon Country Science Committee. As a permanent subcommittee of the Canyon Country Partnership, the Science Committee comprises agency and organizational scientists with interest and knowledge of the canyon country region. The remainder of this paper focuses on work the Science Committee has undertaken regarding land ecology, specifically in the form of a multiyear ecological characterization project for the canyon country region.

Ecological Characterization

The ecological characterization project will result in a comprehensive body of information on the composition, functioning, and potential of the land in the canyon country region. It will provide a scientific foundation for identifying uses that the land is able to maintain. Insofar as possible, the information will be collected and stored in a standardized format, so that it can be shared by all who will use it. Further, this project is *NOT* tied to any specific land-management planning initiative,

potential of the land. The human desires and needs circle represents the products and benefits that society wants from the land. The region where the two circles overlap represents a set of possible land-use allocations that meets human desires and needs, and that the land is able to sustain over the long

but rather is intended to serve as a stand-alone body of information applicable to any planning or management actions that may be undertaken by the agencies in the canyon country region.

Objectives and Structure of Ecological Characterization Project

Two primary objectives underlie the ecological characterization project for the canyon country region:

1. Manage land uses such as recreation, grazing, minerals, etc., at levels that allow sustainability of ecological systems within the bounds of ecosystem function.
2. Conduct a representativeness assessment within the canyon country region that would:
 - a. Identify alternative networks of specific areas, such that each network encompasses the region's entire range of biotic and abiotic variability and is sustainable over the long-term.
 - b. Define the representativeness of any area of interest within the region.

These objectives, particularly the first, recognize that the types and intensities of land uses affect the functioning of landscape units within the region. The following statements therefore represent more specific means of achieving the above objectives:

- Determine the effects of various types and intensities of land uses on ecosystem structure and function.
- Determine the types/intensities of land uses that can be undertaken, in which locations, so that ecosystem structure and function are sustained.
- Determine the extent to which discrete subunits of the canyon country region depend on the context of the surrounding



land (i.e., the whole region) in order to sustain their structure and function.

- Identify prototype areas, at appropriate scales of assessment, where specific project tasks are done first.

The ecological characterization study comprises a stepwise series of tasks and products that are generated over a range of geographic scales. Figure 3 presents a schematic diagram of these project components. Procedures to be used for the project are largely a refinement of methods for work of this type that has been done elsewhere in the country, as reported by

Jensen and Bourgeron (1994) and by Jensen et al. (1996). In other words, proven methodologies developed elsewhere will be applied to the canyon country, recognizing the differences between ecoregions.

As shown in Figure 3, the initial phase of the project involves the definition of terrestrial biophysical environments. This will be done within a prototype area of circa 230,000 hectares, known as the Canyon Country Ecosystem Research Site (CCERS), a subunit of the canyon country region in San Juan County, Utah.

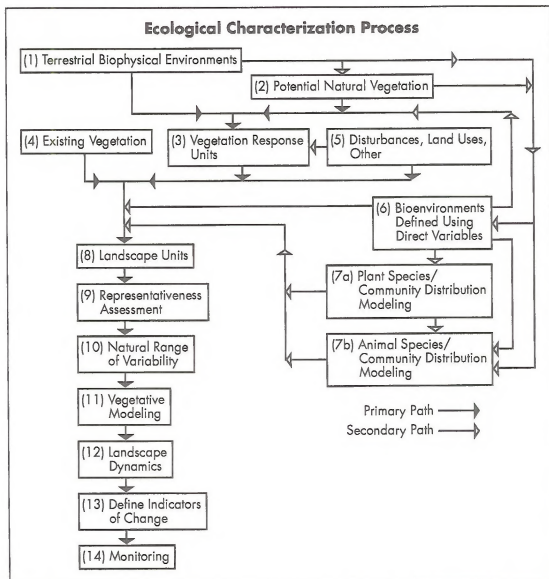


Figure 3. The ecological characterization study comprises a stepwise series of tasks and products that are generated over a range of geographic scales.



Terrestrial biophysical environments are discrete, recurring segments of the landscape that are defined by abiotic variables that influence or "drive" the distribution of biotic features (species and communities). The most commonly used driving variables are elevation, slope aspect, surface geology, and soil type. Individual Geographic Information System (GIS) layers of these variables will be mapped within the CCERS area. These layers will then be superimposed, and each unique combination of elevation range, aspect, lithology, and soil type will define a terrestrial biophysical environment.

A second step in the project is to define and map potential natural vegetation for the CCERS area. This will be done by using models that correlate late- or end-successional vegetation types with their inferred environmental "setting." The biophysical environments and potential natural vegetation data are then merged to define vegetation response units.

Building on these initial products, subsequent phases of the study are increasingly complex and not readily explained in detail in the intended format of this paper. In general, these later phases represent the essence and strength of the characterization. They involve the articulation of disturbance regimes and ecological processes, inference of historic ranges of variability, predictive modeling of vegetation and landscape dynamics, and identification of sensitive indicators or thresholds of ecosystem change.

Usefulness of Characterization Results

The ecological characterization project would essentially define the land ecology circle of Figure 2 for the canyon country region. It represents a scientific foundation that allows decisionmakers to consider the land's ecological potential when addressing land-use planning and management issues. Land managers can use the characterization results to determine if certain land uses are appropriate where proposed, and if use levels are ecologically sustainable.

Specific decisionmaking tools proceeding from the project would include:

- Thresholds of natural ecosystem sustainability.
- Indicators of ecological change for long-term monitoring of the effects of different land uses.
- Identification of the relative scarcity of landscape units, thus providing a regional context for assessing the impacts of specific projects.
- Knowledge of how resistant and resilient various landscape units are to different land uses as a basis for planning that will direct uses toward areas that are naturally capable of handling the impacts and away from sensitive areas that could be irreparably damaged.

One practical application using a very primitive form of characterization procedures has already been done by the Canyon Country Science Committee in a small area near Moab. This study looked at where to put developed campgrounds and designate undeveloped campsites objectively (i.e., not just where people have already created beaten-out camp spots). Factors such as sensitive species sites, high-quality riparian habitat, cultural resources, and sensitive soils were mapped as GIS layers. Social aspects (where people want to camp) and engineering factors (slope steepness, etc.) were also considered. The result was a map of the project area showing polygons of good, moderate, and poor sites in which to allow camping. This project was not tied to any specific planning action, but rather is available for use by the Bureau of Land Management when they need to update or amend the existing Grand Resource Management Plan.

Linking Within and Between Scales

Each level of geographic scope has certain scales of data resolution that are most appropriate



for it. For example, in sites such as the CCERS area, one would focus on collecting and using fine-scale (1:24,000 to 1:100,000) geology, soils, or digital elevation model data. The next level of geographic scope (e.g., the whole canyon country region) is probably best suited to information at scales of 1:100,000 to 1:250,000. The next larger size (e.g., Colorado Plateau, State of Utah) is best suited to scales of 1:250,000 to 1:500,000.

Given the size of the canyon country region, it would be very expensive and time-consuming to produce an ecological characterization (per Figure 3) for the whole region at a fine resolution of detail. A fine-scale characterization that covers the entire Colorado Plateau would be virtually unthinkable in the current climate of limited resources.

For these reasons, the project in the canyon country region uses a technique that we have termed (with apologies to language purists) "multiscale prototyping." An example of this is our initial defining of biophysical environments and potential natural vegetation within a prototype area that is a small subset of the canyon country region—the Canyon Country Ecosystem Research Site—whose area is about 5 percent of the larger region. We believe that eventual characterization results in this smaller area can be extrapolated (as testable hypotheses) to other locations within the canyon country region, and probably also to locations in other parts of the Colorado Plateau. In this way, characterization products generated in a series of smaller areas can (with some limitations) be aggregated to cover their larger contextual regions.

A diagram of possible linkages within and between geographic scales is shown in Figure 4. This diagram can be considered as one site-specific

application of the conceptual framework for integrating the nation's environmental research and monitoring networks, as presented by Bricker and Ruggiero (in press).

The vertical direction in Figure 4 represents increasing geographic size from top to bottom (interscale). For example, the small triangles at the apex on the left represent subunits of the canyon country, such as the CCERS area, San Rafael Swell, or Cisco Desert. The Monument is in the same approximate size range as these canyon country subunits, and thus has the same vertical position in the diagram; subunits of the Monument, such as the Grand Staircase or Escalante Canyons, are represented by smaller apex triangles above the Monument. Subtending trapezoids represent larger regional contexts, such as the canyon country region (Figure 1) or the southwest Utah-Arizona Strip region. The basal trapezoid represents a larger, subcontinental context—in this case, the entire Colorado Plateau Province that includes both the canyon country and southwest Utah-Arizona Strip regions.

The idea of multiscale prototyping is to use characterization of the CCERS area as a prototype for the canyon country region. Subsequent or concurrent characterization of

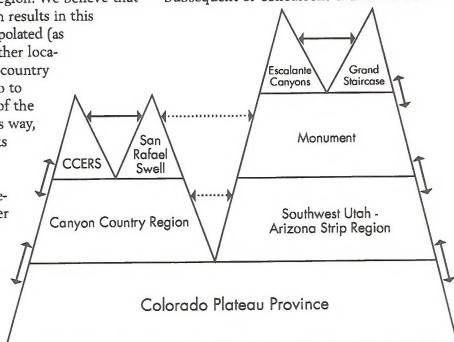


Figure 4. A number of potential linkages exist within and between different scales of ecological characterization, as shown by examples from the Colorado Plateau Province.



similarly sized portions of the canyon country (e.g., San Rafael Swell, Cisco Desert) eventually enables one to extrapolate across the entire canyon country region by making and testing inferences about ecological structure and function within the "in-between" areas. An analogous procedure within the Monument might start with an ecological characterization of the Grand Staircase, moving on to the Kaiparowits Plateau, and eventually extrapolating to the whole Monument.

At a larger scale, an amalgamated characterization for the canyon country region could serve as a prototype for the entire Colorado Plateau. Similar characterization of the southwest Utah-Arizona Strip and other regions of the Plateau would eventually enable extrapolation of ecological characterization results across the whole Plateau.

The horizontal direction in Figure 4 represents discrete areas of similar geographic size (intra-scale). In a large but relatively homogeneous area such as the Colorado Plateau, it may be possible that characterization results reached at the CCERS site or the canyon country region can be extrapolated (as testable hypotheses) "sideways" to other similarly sized, but more distant areas, e.g., CCERS to the Monument, or canyon country region to the southwest Utah-Arizona Strip region.

We believe that the ecological characterization study of the canyon country region could be highly useful to the Monument. We have designed the study as a nested process, scaling upward from intensive site-specific (CCERS) research efforts to regional (canyon country) testing of these results. The study also involves research and monitoring at the regional level that can be scaled upward to monitoring and assessment at the larger province level (the Colorado Plateau).

Results of work at the CCERS and canyon country scales could be applied directly to similar systems in the Monument as hypotheses that predict conditions and responses to perturbations. These hypotheses could be tested in the Monument; if the predictions are

accurate, ecological characterization of the Monument and surrounding region (i.e., by exporting the methodology from the canyon country) could proceed much more quickly and cost-efficiently. Ecological characterization of the Monument could then concentrate on areas that differ most from the canyon country region of the Colorado Plateau. As ecological characterization of the Monument is scaled out to gain perspective of the Monument within its regional context (e.g., at a scale similar to the 5-million-hectare canyon country region), then much of the northern Colorado Plateau will be covered, and characterization of the entire Colorado Plateau can proceed much more efficiently.

Conclusion

Neither the canyon country region nor the Grand Staircase-Escalante National Monument exists in a vacuum. We believe that the ongoing ecological characterization effort in the canyon country region can be extremely useful to the Monument for at least two reasons:

1. Characterization results may be extrapolated as testable hypotheses from the canyon country region to portions of the Monument that are similar. Using the same methods, characterization of the Monument can then concentrate on portions that are least similar to the canyon country.
2. The canyon country characterization project will involve an interactive network of agency and academic scientists whose long-term interests will likely be sufficiently broad in scope to include part or all of the Monument as well.

We believe that the canyon country ecological characterization project can serve as a model for similar scientific work in the Monument. Eventually, we believe that such characterization of the Monument would be useful in planning for sustainable land management there. Further, the successful conduct of



ecological characterization studies in the canyon country and the Monument would contribute to the "ratcheting up" of this component of sustainable land management to the whole Colorado Plateau.

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GEOLOGY







Hydrocarbon Potential in the Grand Staircase-Escalante National Monument, Utah

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ABSTRACT

■ The Grand Staircase-Escalante National Monument contains all the elements necessary for major oil and gas accumulations: source rocks, reservoir rocks, and trapping mechanisms. Although the characteristics of the Monument and Kaiparowits basin as a whole are favorable for the accumulation of oil and gas, wildcat well density is extremely low. Only 47 exploratory wells have been drilled within the Monument, an average of 57 square miles per well.

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Known source rocks of Precambrian, Mississippian, and Permian ages are present within and around the Monument. Carrier formations and major faults can provide migration pathways through which oil and gas generated from these source rocks could have migrated into reservoirs and traps in the Monument. The Proterozoic (Precambrian) Chuar Group of the Grand Canyon Supergroup represents the greatest untested source of hydrocarbons in the Monument. Using source-rock volumetrics and applying an entrapment rate of 10 percent (the typical success rate for exploratory wells) for a 150-square-mile area within the Monument along the axis of the Kaiparowits basin, potential trapped oil in-place could be 270 million barrels or more within the Monument from the Chuar alone. Potential reservoirs in the Monument are the Precambrian Chuar Group, Cambrian Tapeats Sandstone, Mississippian Redwall Limestone, Permian Kaibab Formation, and Timpoweap Member of the Triassic Moenkopi Formation.

Basement- or Chuar-cored surface anticlines observed within the Monument are the potential traps for both Precambrian-source and hydrodynamically displaced oil (where the fluid-potential gradient is such that the flow of water is directed down dip, barring the up-dip movement of oil). The Monument contains at least 24 major anticlines, many tens of miles long. Numerous subsidiary closures are likely to be present along these structures. Only three wells have penetrated through the Cambrian Tapeats Sandstone and into Precambrian rocks on major anticlines in the Monument.

Commercial deposits of oil were discovered in 1964 both within and along the margins of the Monument at Upper Valley field. The Redwall Limestone, Kaibab Formation, and Timpoweap Member of the Moenkopi Formation are productive. The field has produced 25,144,770 barrels of oil, ranking it as the ninth largest oil field in Utah in terms of total production. There are 22 active wells in the field; five of these wells lie within the Monument and accounted for nearly



27 percent of the field production in 1996, and 10 percent of the total cumulative field production. In total, the Monument wells would be ranked as the eighteenth largest field in Utah in terms of cumulative production.

In the final analysis, Precambrian-source and hydrodynamically displaced oil in the Monument can only be proved by drilling exploratory wells and using state-of-the-art techniques to develop any petroleum resources discovered. Three unsuccessful wells penetrating the Precambrian and another 44 plugged wells in shallower targets cannot be used alone to rule out the possibility of major petroleum accumulations in the Monument.

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Geology, Geography, and Resources of the Grand Staircase-Escalante National Monument, Utah

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ABSTRACT

■ Most Utah National Parks and Monuments are founded on magnificent or unusual displays of geology. The Grand Staircase-Escalante National Monument (GSENM), located on the north flank of the Grand Canyon uplift, is no exception. Regionally, the mostly Mesozoic strata of the GSENM slope gently to the north. The regional elevation increases northward as the uneroded pile of geologic formations builds. North-northwest- and north-northeast-trending faults, monoclines, synclines, and anticlines are superimposed on this geologic slope, creating exciting and unusual displays of the geology.

Structurally and physiographically the GSENM is divisible into three parts: the Grand Staircase to the west, the Kaiparowits Plateau in the middle, and the Escalante Canyons to the east. Erosion on the north flank of the Grand Canyon uplift has worked on alternating soft and hard rocks, creating cliffs and slopes or a "staircase" that is most pronounced west of the East Kaibab monocline (Cockscomb). The cliffs form the "risers" of the staircase and are named after the dominant color of the rock. Topographically, the Kaiparowits Plateau is high, but structurally it is a "sunken" region that contains a greater thickness of sediments (strata). It is an undulating area of plateau surfaces incised in places by steep-walled canyons. Fiftermile Mountain, a nearly unbroken cliff extending from Escalante to Hole-in-the-Rock, marks the east edge of the Plateau. Strata gradually rise eastward from Fiftermile Mountain to the Circle Cliffs, an uplift which dominates the Escalante Canyons region of the GSENM. The Circle Cliffs end abruptly to the east along the Waterpocket Fold of Capitol Reef National Park. Deep, rugged, and steep-walled canyons have been carved into the west flank of the Circle Cliffs uplift by the drainages of the Escalante River.

In addition to the scenery, the GSENM contains economic resources that have scarcely been explored or tapped. The western area is known to contain petrified wood, building stone, sand and gravel, manganese, precious and base metals, gypsum, and uranium. The Kaiparowits Plateau has produced petroleum, contains the largest untapped coal resource in the United States, and is a potential source of titanium and zirconium. The Escalante Canyons



contain uranium, petrified wood, and large tar-sand resources. The Navajo Sandstone, which forms the white cliffs "riser" of the Grand Staircase, and into which the Escalante Canyons are eroded, is the most valuable aquifer in southern Utah.



Titanium-Zirconium-Bearing Fossil Placer Deposits in the Cretaceous Straight Cliffs Formation, Garfield and Kane Counties, Utah

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ABSTRACT

■ At least 14 titanium-zirconium-bearing heavy mineral occurrences are known in the Kaiparowits Plateau region of southern Utah. The occurrences are fossil beach placers in the John Henry Member of the Cretaceous Straight Cliffs Formation. They occur at several stratigraphic horizons usually at the top of thick, fine-grained, marine sandstone sequences. The heavy mineral zones are elongate lenses, generally 100 to 300 feet wide, 200 to more than 4,500 feet long, and 4 to 12 or more feet thick. Typically, they can be subdivided into three vertical zones representing middle to upper shoreface, foreshore, and possibly backshore environments. Zones include a lower zone of white, friable, cross-bedded sandstone (3 to 8 percent heavy minerals); a middle zone of red to brown, horizontally bedded sandstone (20 to 60 or more percent heavy minerals); and an upper zone of maroon to black, strongly cemented, massive sandstone (30 to 60 or more percent heavy minerals). Zircon and various titanium-bearing minerals (ilmenite, leucoxene, anatase-brookite, and rutile) are the predominant minerals in the black sand. High-density silicates, oxides, and phosphates are present in subordinate amounts. Only two occurrences, the Mann-Longshot and Calf Canyon, have been studied in any detail. Each contains an estimated 300,000 or more tons of ore of potentially economic grade.

Hheavy mineral (black sand) deposits are common within upper Cretaceous sedimentary rocks of the Western Interior. Deposits are found in Montana, Wyoming, Utah, Colorado, New Mexico, and Arizona (Houston and Murphy, 1977). They are fossil beach placer deposits developed along the western edge of the Cretaceous Interior Seaway. The deposits consist mostly of iron-titanium oxides and zircon with lesser amounts of heavy mineral silicates [garnet, aluminum silicate (Al_2SiO_5)

polymorphs, and staurolite], heavy mineral oxides (chromite, rutile, and spinel), and heavy mineral phosphates (monazite and apatite).

At least 14 titanium- and zirconium-bearing black sand occurrences are known in the Kaiparowits Plateau region of southern Utah (Dow and Batty, 1961). The Kaiparowits occurrences are richer in zircon, and overall, appear to be higher grade than most of the other black sand occurrences in the Rocky Mountain region, often containing 60 percent



or more heavy minerals, with zircon contents of 6 to more than 15 percent.

Location of Deposits

Two separate groups of known deposits are located in the Kaiparowits Plateau region of

southeastern Utah (Figure 1). Within each group, one to three favorable trends have been recognized, and each favorable trend may contain several discrete heavy mineral occurrences. The favorable trends are from 3,000 to more than 7,000 feet wide.

The southern group is located in northern Kane County and consists of three subparallel

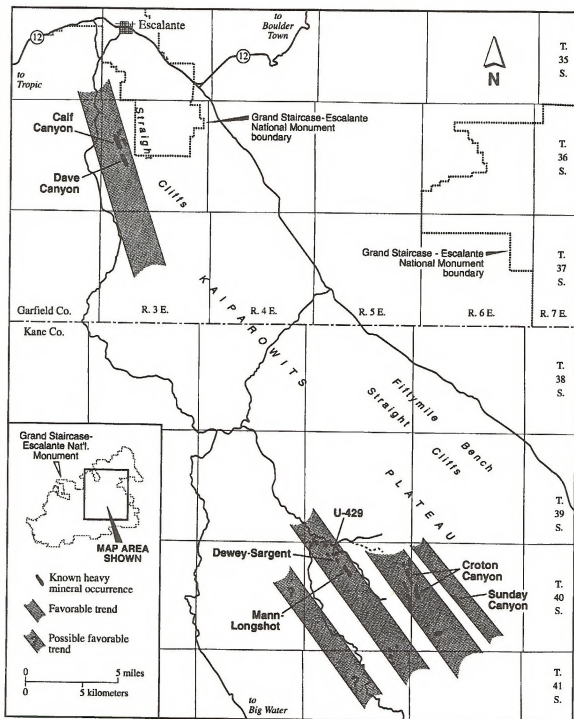


Figure 1. Known heavy mineral deposits and favorable trends.



trends: 1) an eastern trend containing the Sunday Canyon occurrences, 2) a central trend containing the Croton Canyon occurrences, and 3) a western trend containing the Mann-Longshot, Dewey-Sargent, U-429, and other occurrences (Figure 1). Recent exploration suggests a possible additional fourth zone even farther to the west. The favorable trends or zones in the southern group trend N. 40° W. Individual deposits such as the Mann-Longshot trend the same where their orientation can be determined.

The northern group is located in southern Garfield County several miles south of Escalante. This group consists of a single trend, which includes the Calf Canyon and Dave Canyon deposits. Recent exploration expanded the width of the favorable zone and increased its length both north and south. Individual occurrences in the northern group trend N. 15° W.

Additional heavy mineral occurrences could be present along the trend between the two known groups. The absence of known occurrences in this area may be due to: 1) younger stratigraphic units (Tibbet Canyon Member of Straight Cliffs Formation; Wahweap Formation) covering the favorable stratigraphic horizons, and 2) more difficult access to exposures of the favorable horizons.

Exploration and Development History

Geologists and prospectors have done little systematic exploration on the known occurrences in the Kaiparowits region, and they have only recently begun searching for new deposits. Much of the recent exploration has been directed at stratigraphic horizons other than those associated with the known deposits. Little has been written on the deposits and the more recent reports (Doelling, 1975; Doelling and Davis, 1989) mostly summarize the earlier work. This report summarizes much of the earlier work, but also includes new information

collected during recent reconnaissance studies and drilling and sampling programs by exploration companies on two of the known occurrences.

Most of the Kaiparowits heavy mineral occurrences were discovered in the early to mid-1950's during the uranium boom. Between 1957 and 1960, many of the deposits were examined by the United States Bureau of Mines and the results reported by Dow and Batty (1961). There was renewed interest in the occurrences in the mid- to late 1980's, possibly due to the increased price and demand for zircon. Many of the properties were restaked by Rare Tech Industries, which subsequently leased them to Mountain States Resources Corporation. In late 1988, Mountain States received a development grant from the State of Utah and Garfield County to evaluate and develop the deposits. They used the funds to core drill the Longshot-Mann property; expose, trench, and sample the Calf Canyon deposit; and assay and metallurgically test the samples. They subsequently allowed the claims to lapse, possibly due to a drop in zircon prices. In 1996, 3R Minerals restaked the Calf Canyon and Dave Canyon areas, and in 1996-1997, acquired a number of State leases. The State leases were acquired after the Grand Staircase-Escalante National Monument was established, which closed that area to mineral location on Federal land.

Geology of Heavy Mineral Occurrences

Stratigraphy and Depositional Environment

The heavy minerals occur in the John Henry Member of the Cretaceous Straight Cliffs Formation. In the heavy mineral-bearing areas, the John Henry Member is about 700 to 1,100 feet thick, becoming thicker to the northeast (Peterson, 1969; Zeller, 1973a, b, 1990a, b). The John Henry Member consists of a series of five to seven transgressive-



regressive marine sandstones interbedded with nonmarine siltstone, fine-grained sandstone, carbonaceous shale, and coal (Peterson, 1969). Three marine sandstone units (A, B, and G sandstones) are well-exposed in the area and are useful markers (Figure 2). Other stratigraphic markers include the Christensen, Rees, and Alvey coal zones (Figure 2).

According to Peterson (1969), each marine sandstone sequence is characterized by a fairly regular progression from: 1) a lower zone with horizontal stratification and low-angle, medium- to large-scale cross-bedding, to 2) a middle zone with low- and high-angle, medium-scale trough cross-stratification, to 3) an upper zone with horizontal stratification and very low-angle, medium- to large-scale, wedge/planar cross-bedding. These zones have been interpreted as representing middle to upper shoreface and foreshore environments, respectively. Heavy mineral concentrations are found at the top of some of these marine sequences in the upper zone (3) and the uppermost part of the middle zone (2) representing upper shoreface, foreshore, and possibly backshore environments.

According to Houston and Murphy (1977), the heavy mineral deposits in Cretaceous formations of the Rocky Mountains are restricted to regressive depositional sequences usually deposited after maximum marine transgression. Houston and Murphy (1977) also believe that most of the high-grade zones represent storm deposits in the swash zone of the foreshore environment.

Southern Area

Seven heavy mineral horizons are known in the southern area (Figure 2). Three occur at or near the top of thick, white, medium- to fine-grained, friable sandstone (B, F(?), and G sandstone). The B sandstone contains most of the occurrences described by Dow and Batty (1961) and includes the Mann-Longshot, Croton (Rogers) Canyon, Dewey-Sargent, and U-429 deposits. The heavy mineral concentrations are in friable to cemented, generally planar-bedded, fine-grained sandstone. They are less than 3 to more than 12 feet thick and contain 10 to over 60 percent heavy minerals.

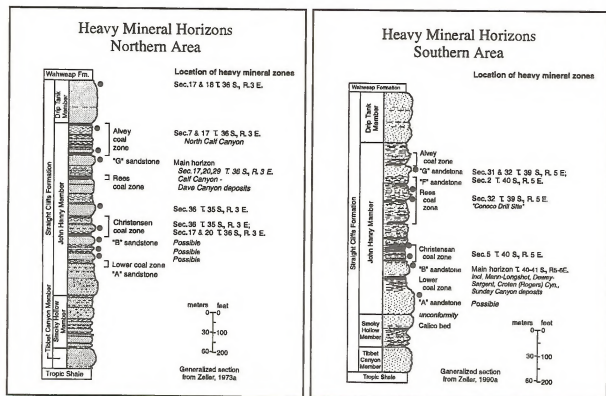


Figure 2. Stratigraphic sections of Cretaceous Straight Cliffs Formation showing heavy mineral-bearing zones. Stratigraphic locations of heavy mineral zones are indicated by black dots; coal zones are shown with brackets.



The other two "sandstone" zones were discovered by 3R Minerals. The lower zone is a 3- to 5-foot-thick, tan, medium- to fine-grained, generally planar-bedded sandstone at the top of a 30- to 40-foot-thick, white sandstone within the middle part of the Rees coal zone. This tan sandstone contains 10 to 20 percent heavy minerals according to 3R Minerals. The upper zone is at the top of the G sandstone. It is 4 to 6 feet thick and consists of a 3- to 5-foot-thick, orange-brown to gray-brown, planar-bedded, friable, fine- to medium-grained sandstone overlain by 1- to 3-foot thick, red to brown, moderately hematite-cemented, fine-grained sandstone. This zone contains 20 to 40 percent heavy minerals according to 3R Minerals.

Four additional anomalous zones are present in the southern area. They are significantly different from typical "beach placers." Three zones are in the Christensen coal zone at 15, 30, (combined in Figure 2) and about 100 feet above the B sandstone. They consist of 1- to 4-foot thick, orange to buff, fine- to very fine-grained, moderately carbonate-cemented sandstone and siltstone. They form blocky, ledgy outcrops in contrast to the poor exposure of most of the Christensen zone. The units are moderately to strongly magnetic and weakly radioactive (1.5 to 1.8 times background). Assay results are not yet available, so TiO_2 and ZrO_2 contents are not known. The fourth zone discovered by 3R Minerals is geologically similar to the other three, but is not magnetic or radioactive. It occurs immediately above a 4-foot-thick coal in the middle of the Rees coal zone.

Northern Area

Five to possibly seven or more heavy mineral zones may be present in the northern area (Figure 2). The main zone is at the top of the G sandstone immediately below the Alvey coal zone. Most of the occurrences in the Dave Canyon and Calf Canyon areas are in this zone. The heavy mineral concentrations are in gray-tan to brown to red-brown, friable to strongly hematite-cemented, fine-grained sandstone. Individual zones are from 3 to 12

or more feet thick. In the Calf Canyon area, the individual zones occur as a number of stacked, en-echelon lenses becoming slightly younger and slightly higher stratigraphically to the east. At least four lenses have been recognized, and it is likely that additional lenses are present. The heavy mineral zones contain from 20 to more than 60 percent heavy minerals.

A number of other heavy mineral zones both above and below the main G sandstone horizon were identified by 3R Minerals during reconnaissance exploration (Figure 2). The zones reported by 3R Minerals are listed below from oldest to youngest:

Zone 1. Five-foot-thick, gray to tan, laminated to planar-bedded, medium-grained sandstone. The sandstone is above a white marine sandstone within the Christensen coal zone in the eastern Calf Creek area. A random sample contained 41 percent heavy minerals and assayed 8.0 percent ZrO_2 and 14.5 percent TiO_2 .

Zone 2. Five- to ten-foot-thick, gray to buff, laminated, fine-grained sandstone. The sandstone is at the top of a thick, white, marine sandstone that occurs above the Christensen coal zone in the Coal Canyon area. Samples contain 10 to 20 percent heavy minerals; no assays are available at present.

Zone 3. G sandstone occurrences described above.

Zone 4. Three- to five-foot-thick, gray to buff, weakly to moderately cemented, fine-grained sandstone. The sandstone occurs at the top of a tan sandstone within the Alvey coal zone in the northern Calf Canyon area. Selected samples contained 40 to 50 percent heavy minerals and assayed 4 to 11 percent ZrO_2 and 5 to 17 percent TiO_2 .

Zone 5. Brown to red, medium-grained, hematite-cemented sandstone. Sandstone occurs at or near the top of the Drip Tank Member of Straight Cliffs Formation or within the lower part of Wahweap



Formation on the north side of Dave Canyon. Selected grab samples assayed 13 to 25 percent ZrO_2 and 20 to 25 percent TiO_2 .

Additional work is required, particularly on the recently identified heavy mineral zones, to determine their stratigraphic position, depositional environment, extent, and heavy mineral content. The estimates of heavy mineral content and assays are from only a few select samples and may not necessarily represent the entire heavy mineral zone.

Description of Heavy Mineral Occurrences

The heavy mineral occurrences are linear, lens-shaped bodies generally with exposed widths of 100 to 300 feet. The obvious heavy mineral zones are from 200 to more than 4,500 feet long and from 4 to more than 12 feet thick. Recent work, however, indicates that significant heavy mineral concentrations, particularly of zircon, may be present in the underlying, less obviously mineralized sandstone, and that ore thickness of up to 25 feet or more is possible. The heavy mineral zones may occur as single lenses separated from other subparallel lenses by barren zones 500 to 800 feet wide or as a series of en-echelon overlapping lenses. The single separate lens style appears to be characteristic of the southern occurrences, whereas the overlapping en-echelon type is well-developed in the northern occurrences at Calf Canyon. Where several complete or incomplete cycles (see below) overlap, the ore zone can be 25 to 30 feet thick.

The heavy mineral-bearing unit usually can be subdivided into three zones (Figure 3):

- 1) an upper zone of dark maroon to black, moderately to strongly

cemented, fine-grained sandstone with mostly planar horizontal bedding,

- 2) a middle zone of brownish gray to purplish gray, generally friable, fine-grained sandstone characterized by horizontal bedding and minor very low-angle cross-bedding, and
- 3) a lower zone of white, friable, medium- to fine-grained sandstone with abundant medium- to high-angle planar and trough cross-bedding.

The zones are interpreted as representing from top to bottom: 1) foreshore to possibly

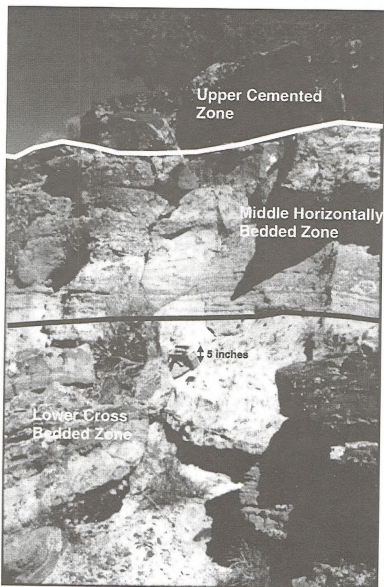


Figure 3. Typical zonation of heavy mineral deposits in Kaiparowits Plateau, Utah, Longshot-Mann deposit. Scintillometer for scale is 5 inches high.



backshore, 2) foreshore (beach swash zone), and 3) upper shore face probably above the breaker zone environments. The eolian dune facies apparently is rare or absent in the Kaiparowits heavy mineral occurrences.

The lower white zone shows the least variation. It is a fine-grained, friable sandstone with moderate- to high-angle planar and trough cross-bedding. Much of the sandstone is structureless, particularly in the lower parts, possibly due to bioturbation. The upper 2 to 8 feet of the lower white contain an estimated 1 to 3 percent dark grains (heavy minerals) and an estimated 2 to 5 percent fluorescent zircon. Most of the dark grains and the zircon are disseminated throughout the sandstone and are only locally concentrated along bedding planes or cross beds. Both the zircon and dark heavy minerals become more abundant up stratigraphic section.

The middle horizontally bedded zone is highly variable. It is generally tan to brownish-gray to purplish-gray, fine-grained sandstone, slightly finer grained than the underlying white sandstone. It is uncemented to weakly cemented, but less friable than the underlying white sandstone. It is generally horizontally planar-bedded, often consisting of alternating medium-bedded sandstone and thinly bedded to laminated sandstone. Very low-angle wedge to planar cross-bedding, trough cross-bedding, and scours are locally present. The scours may represent return channels in the foreshore or troughs behind sand ridges. The zircon and heavy minerals are both disseminated throughout the sand and concentrated along bedding planes or lamella. The heavy mineral lamella range from less than 0.05 to 0.5 inches (1 to 12 mm) thick and contain an estimated 10 to possibly 30 percent dark opaque minerals and 20 to 40 percent fluorescent zircon. The heavy mineral lamella are often moderately hematite-cemented, but overall the zone is still friable. The sandstone between the heavy mineral lamella contains an estimated 3 to 15 percent disseminated opaque minerals and an estimated 5 to 25 percent disseminated zircon. The number and thickness of heavy mineral lamella generally increases upward as does the

overall heavy mineral content. The thickness of this middle zone is variable, usually between 4 and 10 feet for a single (nonoverlapping) zone.

The upper cemented zone is a dark purple to maroon to black, strongly hematite-cemented, fine-grained sandstone. It usually forms a resistant ledge at the top of the sandstone sequence and often forms a "dip slope" pavement. The upper cemented zone usually does not show well-developed bedding; either it never developed or was later destroyed by cementation. The bedding that is present is horizontal. The heavy minerals appear to be fairly well-disseminated throughout the sandstone with only minor local concentrations along bedding. The cemented sandstone contains an estimated 30 percent opaque minerals and an estimated 30 to possibly 40 percent fluorescent zircon. The upper cemented zone is usually only 2 to 5 feet thick.

The heavy mineral content of the sandstones is quite variable and changes drastically both laterally and vertically. To determine the average grade of a deposit will require numerous, fairly closely spaced samples. Individual samples may give some indication of the type and range of values to expect, but are inadequate for determining the overall grade of any occurrence. Table 1 shows the ranges and average titanium and zirconium content of samples collected from the Mann-Longshot and Calf Canyon deposit by various workers and indicates the amount of variability between individual samples.

Mineralogy and Alteration

Most of the detailed work on the mineralogy of the heavy minerals has been done by consulting firms as part of studies on beneficiation and recovery techniques. Studies have been done on samples from the Mann-Longshot, Sargent, and Calf Creek deposits by Carpco, Inc., and Hazen Research. Most of the following section is taken from their reports (Carpco, Inc., 1987; Hazen Research, Inc., 1988a, b).



Table 1. Summary of titanium and zirconium assay results for Mann-Longshot and Calf Canyon heavy mineral deposits.

	Grade of Selected Heavy Mineral Zones			
	Range (percent)		Average (percent)	
	ZrO ₂	TiO ₂	ZrO ₂	TiO ₂
<i>Mann-Longshot Deposit</i>				
Park (1989) (137 drill samples)	0.1 - 11.0	0.3 - 28.2	3.0	9.6
Dow and Batty (1961) (2 surface samples)	3.1 - 9.5	13.0 - 28.4	-	-
<i>Calf Canyon Deposit</i>				
3R Minerals (1996) (9 surface samples)	5.8 - 25.4	7.2 - 27.7	15.8	20.9
Dow and Batty (1961) (2 surface samples)	6.5 - 18.1	13.4 - 24.1	-	-
Doelling (1975) (8 surface samples)	0.1 - 13.5	0.8 - 20.8	-	-

Heavy minerals in the deposits are predominantly zircon, various titanium-bearing minerals including ilmenite; altered ilmenite (leucosene or pseudorutile), secondary TiO₂ minerals such as anatase and brookite, and primary detrital rutile. Together these minerals comprise 50 to over 80 percent of the heavy mineral fraction. The remaining fraction consists of hematite and manganese oxides, various heavy

mineral silicates including garnet, tourmaline, staurolite, aluminum silicate (Al₂SiO₅) polymorphs, and sphene, heavy mineral phosphates including monazite and apatite, chromite, and zinc spinel (gahnite). Magnetite was not reported. Some gold [up to 0.04 ounces/ton (Doelling and Davis, 1989)] and platinum group elements (PGEs) [0.X to XX ppm (Reeves, 1997)] have been reported, but only a few samples have been assayed. Niobium (0.0X percent Nb₂O₅), tantalum (0.0X to 0.X percent Ta₂O₅), and tungsten (0.0X percent WO₃) are also present, but only a few assays are available (R. Reeves, 1997, e-mail).

Results of microprobe analysis of heavy mineral concentrates from the Mann-Longshot, Sargent, and Calf Canyon deposits are shown in Table 2. A minimum of 300 grains were counted with modal analysis (mineral identification) made using a semiquantitative energy dispersive technique with a modified

Table 2. Microprobe analysis of heavy mineral fractions of samples from Mann-Longshot, Sargent, and Calf Canyon heavy mineral deposits, Garfield and Kane Counties, Utah [after Carpcio, Inc., 1987].

Microprobe Analysis of Heavy Mineral Concentrates (weight percent)								
	Monn-Longshot				Sargent		Calf Canyon	
Heavy Minerals								
>95% TiO ₂ ("Rutile")	31.6	27.2	19.5	27.6	25.7	15.2	5.5	3.4
85-95% TiO ₂ ("Leucaxene")	-	1.0	-	1.6	-	1.6	0.9	0.3
65-85% TiO ₂ ("Illeucaxene")	1.7	5.4	0.4	2.3	1.7	0.7	3.2	7.9
57-65% TiO ₂ ("Ilmenite")	1.7	3.1	2.8	4.4	4.3	4.5	16.6	17.1
<57% TiO ₂ ("Ilmenite")	15.9	20.0	7.3	30.0	19.0	2.1	32.0	18.8
Zircon	17.7	25.4	20.8	19.2	27.3	21.1	23.9	32.9
Monazite	0.4	-	-	-	1.2	0.4	0.4	0.4
Allanite	0.3	0.9	0.3	0.3	0.6	1.1	-	1.3
Intermediate Minerals								
Hematite - Mn oxides	10.6	4.3	8.2	7.0	9.7	5.1	1.8	1.6
Aluminosilicates	0.3	-	-	-	-	-	-	-
Apatite	0.2	-	1.4	-	-	0.3	-	-
Staurolite	2.7	1.3	5.6	-	-	2.5	1.5	2.0
Garnet	1.9	0.5	6.9	0.5	3.0	16.9	4.1	4.1
Entrapped Liquids								
Quartz	13.6	10.1	24.5	4.8	5.6	26.6	10.1	10.0
K Feldspar	-	-	0.9	-	-	0.2	-	-
Calcite	1.2	0.8	0.7	1.4	1.7	1.6	-	-
Head Feed (% heavy minerals)	39.1	66.1	19.1	92.6	86.1	46.0	74.3	25.0



MAC 500s microprobe. Volume percent was recalculated to weight percent using specific gravities for each mineral species. The various titanium divisions partially reflect the degree of alteration of the original detrital ilmenite. With increasing alteration and oxidation, iron is selectively removed from ilmenite leading to progressively higher grade leucoxene. Ultimately, recrystallization and cation mobilization can yield an almost iron-free TiO_2 (Force, 1991). Studies by Hazen Research, Inc., (1988a) on three samples indicate the titanium occurs as residual ilmenite, leucoxene (pseudorutile), secondary recrystallized anatase, and brookite and detrital rutile. The anatase and brookite occur as cement and coatings intimately intermixed with iron oxides and as irregular replacements of ilmenite and leucoxene. The ilmenite, rutile, and pseudorutile occur as discrete grains. Hazen did not report the relative percentage for each titanium-bearing mineral.

The analysis by Hazen Research, Inc., (1988a) showed that samples with higher percentages of ferric iron had abundant secondary anatase and brookite, but that samples with lower ferric iron contained mostly unaltered or partially altered ilmenite. This relationship indicates that most of the alteration and "upgrading" of the ilmenite occurred in situ after deposition.

Source of Heavy Minerals

The source of the heavy minerals is not known, but the source area for most of the Straight Cliffs Formation in the Kaiparowits region was to the southwest and consisted of Paleozoic and lower Mesozoic sedimentary rocks. These sedimentary rocks could have contained heavy minerals that had been reworked many times. The relative maturity of the Kaiparowits heavy mineral assemblage (zircon-rutile-ilmenite with little or no magnetite) supports a reworked source for the heavy minerals. The original source could have been Precambrian crystalline rocks and/or Triassic to Jurassic magmatic rocks of western Arizona and southeastern California. Age dating of the detrital zircon could help locate the original source area.

Economic Potential

Various estimates have been made on the size of individual black sand deposits based mostly on measuring the exposed occurrences of visible ore and extrapolating their subsurface extent. The estimates for some of the better deposits range from several hundred thousand tons (Dow and Batty, 1961) to more than 10 million tons of ore (Reeves, 1997). Only a few estimates have been made of the total black sand resource in the Kaiparowits region and they were based on very limited, and generally inadequate, information. Dow and Batty (1961) estimated that less than 1,000,000 tons of black sand ore were contained in the deposits they identified in the Kaiparowits area. More recent work indicates that several of the known deposits are larger than previously thought and that additional black sand occurrences are present in the area. The total black sand tonnage could be significantly larger than Dow and Batty's estimate, but insufficient information is currently available to estimate the total tonnage or grade. Only the Mann-Longshot deposit has been sufficiently investigated to even attempt reserve calculations.

The Mann-Longshot deposit was initially drilled in the late 1950's and was calculated to contain measured, indicated, and inferred reserves of 450,000 to 550,000 tons averaging 11 percent TiO_2 and 22 percent ZrO_2 [Rambo(1965) as referenced by Doelling and Davis (1989)]. The deposit was most recently core drilled in 1987 by Mountain States Resources. Calculated reserves based on this drilling are 300,000 to 310,000 tons at a grade of 3.0 percent ZrO_2 and 9.6 percent TiO_2 (Park, 1989). We consider this second estimate more reliable because of more accurate assaying and sample collection methods. The deposit consists of two horizons: an upper, high-grade, red to black, strongly cemented sandstone (3 to 8 percent ZrO_2 and 15 to 30 percent TiO_2), and a lower, reddish-brown to yellow-brown, friable sandstone with considerably lower grades (1 to 3 percent ZrO_2 and 5 to 10 percent TiO_2). The deposit may be



somewhat larger since many of the holes, particularly in the thicker, central part of the deposit, stopped in ore-grade material and the deeper parts of other holes were not sampled or assayed by Mountain States Resources.

Surface mapping and preliminary sampling by 3R Minerals and others indicate that the Calf Canyon deposit contains a significant resource worthy of additional investigation. Rough estimates based on the dimensions of the exposed heavy mineral zones suggest 300,000 to possibly 600,000 tons or more of ore are present with a higher zirconium and titanium grade than the Longshot-Mann deposit. Detailed mapping, close-spaced systematic surface sampling, and some drilling are needed for an accurate assessment of the size and grade of the deposit.

The other black sand occurrences (Croton Canyon, Sunday Canyon, U-429) have not been sufficiently studied to estimate resource size, although the dimensions reported by Dow and Batty (1961) of 200 to 300 feet wide by 200 to 600 feet long by 4 to 8 feet thick for several deposits are only slightly smaller than those reported for the Calf Canyon deposit.

Future

The future of development of the titanium-zirconium heavy mineral deposits in the Grand Staircase-Escalante National Monument is uncertain and depends partly on how the United States Bureau of Land Management ultimately manages the Monument. Two black sand occurrences (Mann-Longshot and Calf Canyon) are large and rich enough for a potentially economic mining operation. Some of the other less investigated occurrences may be equally attractive. Most of the known occurrences in the Monument are on Federal land, so permitting a mine would be difficult. However, some of the more recently identified occurrences are on Utah State inholdings and might be less difficult to permit and develop.

From a purely scientific point of view, the black sand deposits and underlying and overlying sandstones present a valuable opportunity to study ancient shoreline depositional processes and paleoenvironments. The deposits: 1) are fairly well-preserved due to a well-cemented protective cap, 2) contain a variety of different sedimentary structures, and 3) exhibit several "stacking sequences" or progression of depositional facies. Detailed studies have been done in similar geologic settings by Houston and Murphy (1977) for the Marias River deposit in Montana, by Bingler (1963) for the Sanostee Mesa deposits in New Mexico and Colorado, and by Zech et al. (1994) for the Point Lookout Sandstone deposits in New Mexico and have yielded valuable scientific results. Similar studies of the southeastern Utah occurrences should be equally instructive.

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Environmental Change in Valleys of the Paria River Basin

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ABSTRACT

■ The wide valleys of the Paria River basin and similar valleys of the Grand Staircase-Escalante National Monument contain relatively thick deposits of alluvium, which is very fine-grained sand for the most part. These valley-fill deposits are extensive, spanning the entire width of the valley between bedrock margins. The deposits are quite young geologically, dating from about 5,000 years at the oldest to 60 years at the youngest. The deposits formed by repeated episodes of valley erosion and stream entrenchment followed by aggradation and buildup of the streambed. Termed cut-and-fill, this process resulted in striking changes in the physical environment of the alluvial valleys.

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The erosional phase, called arroyo cutting throughout the Southwest, is perhaps the most dramatic. Arroyo cutting last occurred in valleys of the Monument beginning around 1880 until 1900-1910. The resulting deepening and widening of stream channels were disastrous for pioneer settlements. Many settlements were abandoned, transportation became increasingly difficult, irrigation ditches were hard or impossible to maintain, and valuable farmland was lost through dissection of the alluvial valleys. Indeed, geologists who witnessed arroyo cutting compared the catastrophic effects to earthquakes and volcanic eruptions. Channels remained in this wide, deep, and unstable condition until the early 1940's when they began to fill through floodplain aggradation. In the Paria River basin, these floodplains total 20 km². This is new and potentially useful land which was formerly the active stream channel.

When the area was settled in the mid- to late 1800's, most streams flowed at or near the surface of the alluvial valleys. At that time, the valleys in the Monument were undergoing a gradual filling that began around A.D. 1400. The filling ended around A.D. 1880 with the beginning of historic arroyo cutting. The resulting valley fill extends across the valleys, except where removed by historic arroyo cutting. Prehistoric archaeologic remains once present on the valley floors were buried beneath several meters of sediment. The fill deposits even extend up small tributaries to the foot of hillslopes where juniper and pinyon trees are partly covered by alluvial and hillslope deposits. This extensive alluviation followed an episode of prehistoric arroyo cutting from around A.D. 1200-1400. The early arroyo cutting was probably the main factor leading to abandonment of southern Utah and northern Arizona by the Anasazi.

The causes of arroyo cutting are open to speculation and much remains to be learned about the rate, timing, and volume of sediment stored and removed by the cut-and-fill process. Climate variation and land use are evidently the main



factors affecting arroyo cutting, although climate is probably the driving force. Historic arroyo cutting happened during a period of unusually frequent, large floods caused by heavy warm-season rainfall. Arroyo cutting was likely exacerbated by settlement of the region, but it seems unlikely that land use was the single cause of stream entrenchment. Regardless of the causes, land managers need to understand that the landscape of the alluvial valleys is not static, even on timescales of a few decades.

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Variation in the Chemistry of Upper Cretaceous, Straight Cliffs Formation Coals

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ABSTRACT

■ Analytical data for more than 700 coal samples from the Straight Cliffs Formation, Kaiparowits Plateau, Utah, have been assembled into a database. Data for outcrop samples as well as samples from an early exploration program were found to be unreliable and should not be used for evaluation of coal quality. The reader is further cautioned that the coal quality values in the database may not be fully representative of the basin wide in-ground coal quality due to the nonuniform, areal sample distribution.

Compositional variation of coals in the Straight Cliffs Formation is explained as a consequence of depositional environment and burial history. A uniform increase of coal rank, from subbituminous B in the north to high-volatile bituminous B in the south, reflects the greater maximum burial depth of the southern coals in the geologic past. Although total sulfur shows substantial interseam variation, a weak trend of increasing sulfur to the northeast is observed. Variation of sulfur content is attributed to proximity of the Late Cretaceous, Western Interior Seaway with locally high values marking early incursions of marine water into the coal-forming peat. Ash yield varies widely and shows no regional trends. High-ash areas within the Christensen zone may indicate locations of temporally persistent paleo-channels, whereas low-ash areas mark locations where raised mires may have been present. Finally, a comparison of coal samples from the Straight Cliffs Formation with coal samples from the Wasatch Plateau reveals substantial overlap of both sulfur and calorific values.

Nearly all of the coal in the Upper Cretaceous, Straight Cliffs Formation is of Coniacian to Santonian age and occurs in four coal zones: the Henderson, Christensen, Rees, and Alvey (Figure 1). These coal-bearing sediments span a 600 to 1,600 foot stratigraphic interval and cover a 1,300 square mile area within the Kaiparowits Plateau. The Straight Cliffs Formation thickens to the north and to the east where abundant shoreline sands form the Straight Cliffs escarpment. This prominent feature marks a persistent, Late Cretaceous paleogeographic boundary, with open-marine environments of the Western Interior Seaway

to the northeast and coal-forming mires and coastal plain environments to the southwest (Hettinger et al., 1996).

Data Sources and Reliability

Our analytical data originate from company reports in U.S. Bureau of Land Management (BLM) and Utah Geological Survey (UGS) files, a few records from Afolter and Hatch (1980), and numerous published records listed in Doelling and Graham (1972). Currently, over 700 analytical records for coal samples

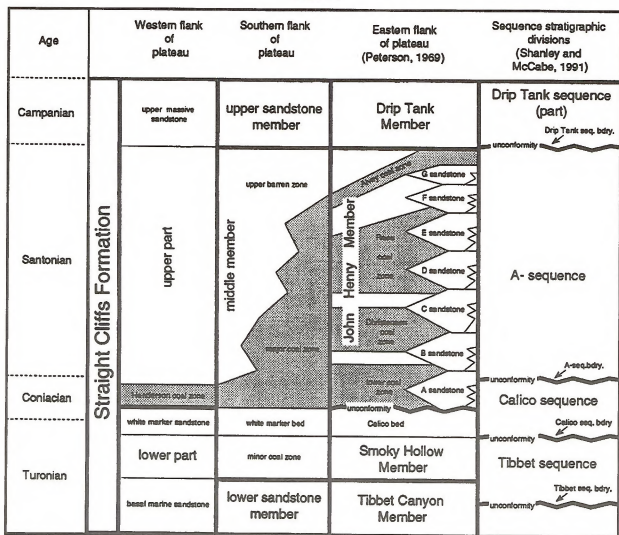


Figure 1. Stratigraphic divisions of the Late Cretaceous, Straight Cliffs Formation in the Kaiparowits Plateau, Utah (from Hettinger et al., 1996).

from the Straight Cliffs Formation are in a Quattro Pro version 6.02 spreadsheet. The location of these coal samples is shown in Figure 2.

Figure 2 shows the widespread, but nonuniform, distribution of coal sample locations. Besides the uneven distribution of sample locations, the thickness and abundance of coal at any given location within the Kaiparowits Plateau also varies (Allison, 1997; Hettinger et al., 1996). Thus, random sampling of the in-ground coal is doubtful, and the data may not be fully representative of the in-ground quality of coal in the Kaiparowits Plateau. Nonetheless, these data do allow a qualitative assessment of

the compositional variation of coal in the Straight Cliffs Formation.

Analytical data examined in this study were generated by different laboratories for different kinds of coal samples. As demonstrated by Hower and his coworkers (1989), building coal databases using data from different sources requires careful scrutiny of both the analytical methods and the sampling procedures. Hence, a preliminary evaluation of the data set was undertaken. Besides examining the database for anomalous values, various cross-plots were made to identify possible systematic bias in the data set. An example of such a cross-plot is provided in Figure 3 where calorific value is compared with moisture.

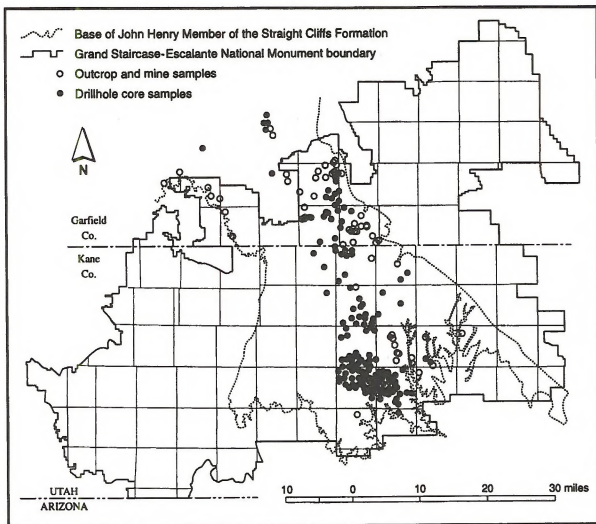


Figure 2. Map showing the location of core, outcrop, and mine samples for coals in the Straight Cliffs Formation, Kaiparowits Plateau, Utah.

Figure 3 shows that most of the data plot along a single trend where the calorific value shows the expected increase with decreasing moisture. Two sets of data deviate from this trend. One deviating cluster of data points originates from samples collected during an early exploration drilling program. The other more scattered set of data originates from outcrop samples. The early exploration core samples exhibit lower moisture contents than expected given their heat content; these data are consistent with core samples that were inadvertently dried prior to analysis. Such dried samples are unreliable indicators of coal rank (ASTM, 1996) and indicate erroneously high rank for affected coals. The deviation of the outcrop samples is consistent with natural weathering. Weathering is well-known to

decrease the heat content of coal (Davidson, 1990) and results in erroneously lower rank than exists for the equivalent buried coal. Both sets of data outliers are excluded from subsequent analysis of the data.

Discussion

Variation of Coal Composition

In this study we examine the regional variation of ash, sulfur, and calorific value of coals found in the Straight Cliffs Formation. The composition of coal is largely a consequence of depositional environment and burial history. Ash yield and sulfur content are largely related to depositional setting, whereas calorific value

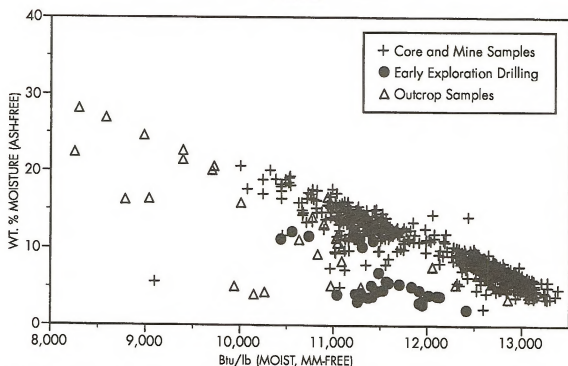


Figure 3. Cross-plot showing how calorific value varies with moisture for 686 coal samples from the Straight Cliffs Formation, Kaiparowits Plateau, Utah. Numerous outcrop samples, as well as a set of core samples from an early drilling program, deviate from trend of core and mine samples.

is a rank parameter related to burial history. Histograms showing the distribution of sulfur, ash, and calorific values for the coal samples are provided in Figure 4.

Rank

We chose the moist, mineral-matter-free gross calorific value (moist, mm-free Btu/lb) calculated according to ASTM method D-388-84 (ASTM, 1987) as an appropriate rank parameter for coals from the Straight Cliffs Formation. This parameter is sensitive to compositional changes through the subbituminous and high-volatile bituminous ranks and is calculated from common analytical data (calorific value, moisture, ash, and total sulfur). The current ASTM standard method for determination of coal rank (ASTM, 1996) was not used since it requires an additional parameter (sulfate content of ash) that was not routinely measured when the Straight Cliffs coal samples were analyzed.

Figure 4C shows the rank distribution of the coal samples and is annotated with ASTM

apparent rank designations. Coal samples with more than 15 percent ash (as-received) were excluded from the figure to avoid error associated with calculation to mineral-matter-free basis. The conspicuous bimodal sample distribution shown in Figure 4C is suggested to be an artifact of the nonuniform distribution of the sample locations (Figure 2).

To simplify delineation of regional rank trends, a single, average calorific value for each core location was calculated by weighting the respective coal intervals encountered in a drill hole according to their thickness. Density of the individual samples was not considered. In 15 drill holes, the resulting weighted-average coal quality reported more than 15 percent ash, and the data for those holes were excluded from subsequent examination of regional rank variation. Regression analysis was undertaken on data for the remaining 149 drill holes using their Universal Transverse Mercator (UTM) easting and UTM northing coordinates as the independent variables and the weighted-average calorific value as the dependent variable. The

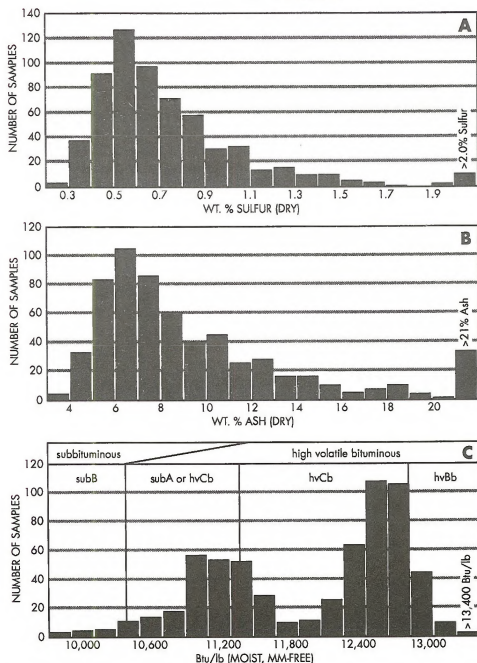


Figure 4. Histograms showing compositional variation of coal samples from the Straight Cliffs Formation, Kaiparowits Plateau, Utah: A) distribution of sulfur content for 622 core and mine samples; B) distribution of ash yield for 622 core and mine samples; C) distribution of calorific values for 556 core and mine samples with less than 15 percent as-received ash. The bimodal distribution is an artifact of the uneven sample distribution. Coal rank designations are according to ASTM (1987) where subB = subbituminous B, subA = subbituminous A, hvCb = high volatile C bituminous, and hvBb = high volatile B bituminous.

resulting first-order trend surface corresponds to the equation:

$$\text{Moist, mm-free Btu/lb} = 18,508 - 0.009292692^{\circ}\text{E} - 0.04093911^{\circ}\text{N} \quad (1)$$

where: E = UTM easting coordinate and, N = UTM northing coordinate. The coefficient of determination (R^2) for the regression is 0.71.

Equation 1 is graphically represented in Figure 5 where the calculated moist, mm-free Btu/lb values are used to delineate ASTM apparent rank categories. Figure 5 shows that rank increases from subbituminous B in the north to high-volatile B bituminous in the south. Either Equation 1 or Figure 5 can be used to estimate coal rank at a given location, but, as discussed below, the actual rank of a coal encountered at that location may vary slightly depending on its relative stratigraphic position.

Hettinger et al. (1996) show that the thickness of the Calico and A sequences of the Straight Cliffs Formation, which contain the four

coal zones of interest (Figure 1), ranges between 600 and 1,500 feet, but is less than 1,000 feet thick over most of the Kaiparowits Plateau. A coal encountered 1,000 feet below a coal assaying 12,000 Btu/lb (moist,

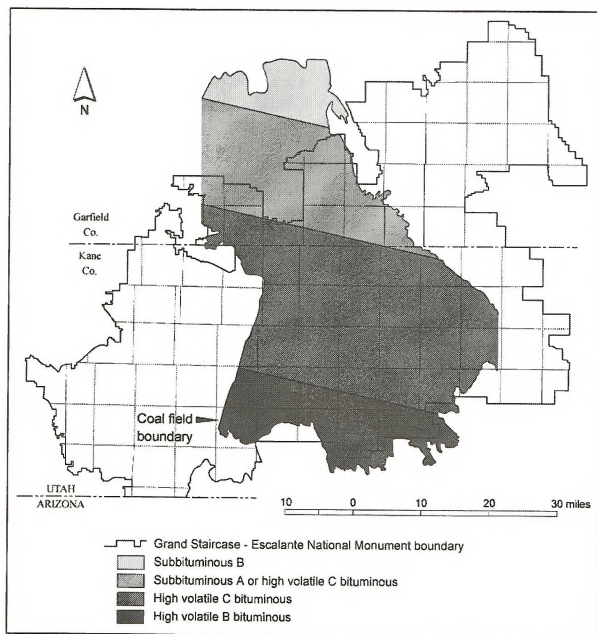


Figure 5. A first-order trend surface of coal rank (ASTM, 1987) within the Straight Cliffs Formation, Kaiparowits Plateau, Utah.

mm-free) will assay about 13,000 Btu/lb according to coalification gradients established for the Illinois Basin (Damberger, 1971). Hence, deviations of as much as ± 500 Btu/lb from the trend shown in Figure 5 might be expected due to the vertical position of an individual coal in the coal-bearing sequence. More study is required to establish a vertical coalification gradient(s) specific to coals in the Kaiparowits Plateau.

Cross-plots of calorific value versus present burial depth (not shown) show no systematic

trend of rank with depth despite the wide range of rank indicated for this area. Lower rank coals in the north are present at nearly the same depths as higher rank coals in the south. Given the apparently smooth regional variation of coal rank across the study area, greater maximum burial depths of southern coals (and greater amounts of subsequent uplift and erosion) likely explain the higher rank in the south.



Sulfur

Sulfur in coal originates from the abundant sulfate ions in seawater via heterotrophic bacterial reduction to hydrogen sulfide that readily combines with iron to form pyrite. In the absence of iron, hydrogen sulfide combines with otherwise labile perhydropyric organic constituents enriching the peat in organically bound sulfur (Casagrande, 1987).

Most of the Straight Cliffs coal samples exhibit low sulfur contents (Figure 4B) with 89 percent of the samples classified as low-sulfur coal according to the definition presented by Wood et al., (1983) (less than 1.0 percent as-received sulfur). A first-order trend surface of total sulfur content, made using weighted-average sulfur values for 167 drill holes as the dependent variable, shows sulfur increasing to the northeast (map not shown). However, the data exhibit a poor fit to this trend ($R^2 = 0.30$).

Despite the poor fit, the general increase of sulfur to the northeast is consistent with the northeastern location of marine water during peat accumulation (see Figure 23 in Roberts and Kirschbaum, 1995).

Figure 6 shows the widely variable sulfur content of 14 coal seams encountered in a drill hole as well as the vertical variation of sulfur within individual seams. The generally low sulfur content of the coal samples (Figure 4B) indicates the coal-forming peat accumulated in strictly freshwater environments and had little contact with sulfate-bearing marine waters after burial. Less common high-sulfur coals likely resulted from brief, syngenetic to early diagenetic incursions of marine water into the peat.

The large interseam variation of sulfur content shown in Figure 6A suggests that, at least for some areas, examination of a restricted strati-

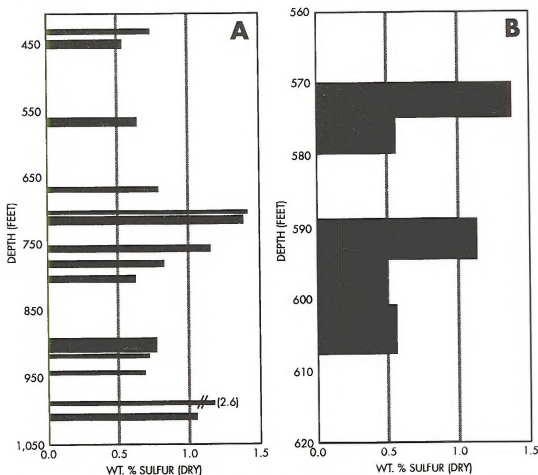


Figure 6. Variation of sulfur for: A) whole seams, and B) partial seams encountered in two drill holes from the Kaiparowits Plateau, Utah. Vertical axis indicates depth below surface.



graphic interval might improve delineation of regional variation of sulfur content. Given the apparent discontinuous nature of the seams and attendant problems with regional seam correlations, investigation of the lateral variation of sulfur for a single seam was not attempted; instead, a weighted, mean-dry-sulfur content of coal seams in the Christensen coal zone was calculated for 134 sample locations. Local seam names, including the Blue, Brown, Red, "K", "L", and "M", were used to identify records and intervals belonging to the Christensen zone in those instances where the coal zone is not noted in the data record. Trend surface analysis again showed sulfur to increase to the northeast, but the fit of the data did not improve. This lack of improvement is attributed, in part, to dual forms of sulfur in coal. The marine signature

due to organic sulfur is diminished where inorganic constituents serve to dilute the organic fraction of coal. Conversely, pyritic sulfur tends to be higher where mineral matter is elevated. Figure 7 is a hand-contoured map showing the lateral variation of sulfur content for coal in the Christensen zone. Locally high sulfur contents are interpreted to mark embayments along the paleo-shoreline that improved access of sulfate ions to the coal forming peat.

Ash

Ash, obtained upon combustion of a coal sample, largely originates from crystalline minerals although organically bound cations are major ash-forming constituents in many subbituminous and lower rank coals.

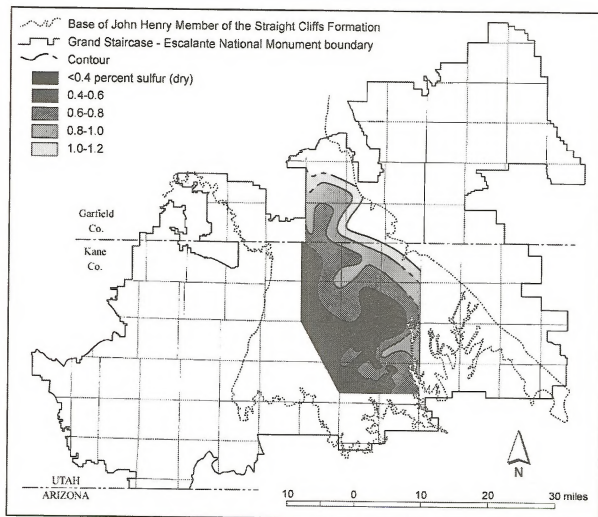


Figure 7. Mean, dry weight percent sulfur isolines for coals in the Christensen coal zone. Base map modified from Allison [1997].



Crystalline minerals in coal have numerous origins, including: fluvial detrital deposits (e.g., mud and silt deposited in the mire during floods), aeolian deposits (e.g., volcanic ash-falls), and neo-formed minerals (e.g., clays, sulfates, and sulfides precipitated in fractures). Organically bound inorganic constituents are largely present as carboxylate salts, dominated by Ca, Mg, and Na, that originate from ground water, dissolution of other minerals, and contributions from plants in the paleo-mire (Ward, 1986).

No regional trend of increasing or decreasing ash yield was noted. The lack of a regional trend can be partly explained by the varied origins of ash-forming constituents discussed above. Another, perhaps more important, reason for the apparent absence of a regional

trend involves the lack of a uniform sampling strategy in instances where mineral-rich partings are present or where the coal gradually grades into surrounding country rock. Finally, as shown for sulfur in Figure 6, substantial inter- and intraseam variation of ash confounds delineation of regional ash trends.

Figure 8 shows variation of ash yield for coals in the Christensen zone and was constructed using the same data set that was used make the sulfur isoline map shown in Figure 7.

Figure 8 reveals that ash is the most spatially variable parameter examined in this study. This variability can be attributed to the multiple origins of ash-forming constituents, and problematic sampling strategy, as well as the inter- and intraseam variation discussed above. Nonetheless, high-ash areas are interpreted to

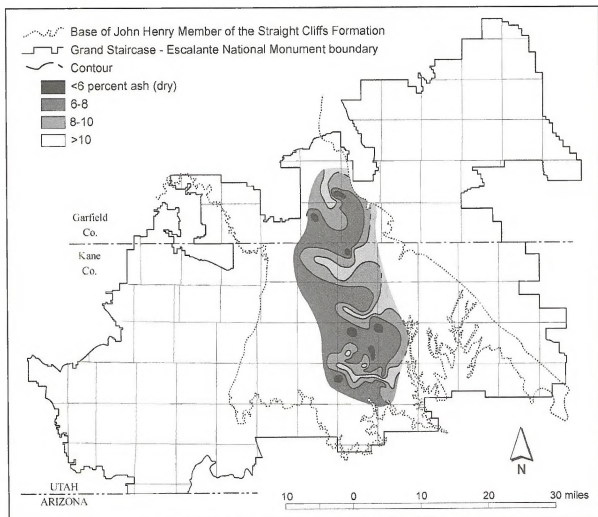


Figure 8. Mean, dry weight percent ash isolines for coals in the Christensen coal zone. Base map modified from Allison (1997).



indicate approximate locations of rivers that carried sediment through the coal-forming mire. Episodic flooding, with attendant mineral-rich overbank and crevasse splay deposits, is thought to have locally increased ash yield adjacent to temporally persistent rivers. Low-ash areas may indicate locations where raised mires restricted detrital input (McCabe and Shanley, 1992). More precise delineation of changes in ash yield requires further examination of the data perhaps augmented by consideration of corresponding well logs and, where available, major element analysis of the ash.

Comparison with Wasatch Plateau Coals

About 90 percent of Utah's current coal production is from coals of the Blackhawk Formation in the Wasatch Plateau coal-field; this coal is largely consumed to generate electricity (Jahanbani, 1996). The abundance of thick, flat-lying seams of high quality coal, which is efficiently produced from underground mines, is no doubt part of the reason Utah enjoys relatively inexpensive electricity. Indeed, Utah ranks 49th by state in per capita expenditure for electricity, with prices 24 percent lower than the national average. Coal-fired powerplants generate 95 percent of the electricity used in Utah (Barrett, 1995).

Figure 9 compares the sulfur content and

calorific value of 470 coal samples from the Straight Cliffs Formation with those of 218 coal samples from the Wasatch Plateau. The data records used for these comparisons are from BLM and UGS files and represent coal core samples for coal beds greater than 5 feet thick. Both sets of samples show uniformly low sulfur contents (Figure 9A). Calorific values for the two sets of samples overlap with samples from the Wasatch Plateau ranging to higher values than those from the Straight Cliffs Formation (Figure 9B). Mathematical calculation using sulfur and calorific value shows that 67 percent of the samples from the Straight Cliffs Formation comply with the U.S.

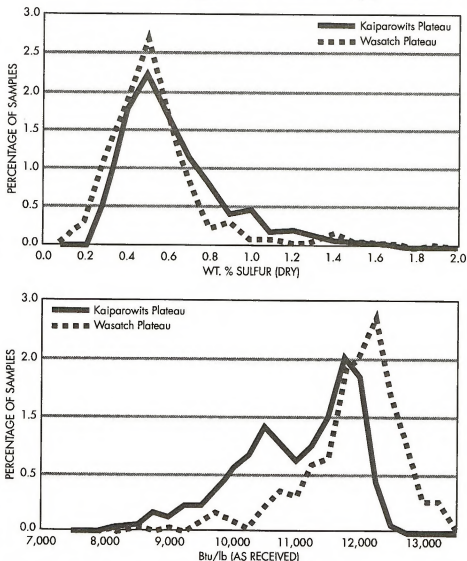


Figure 9. Comparison of the composition of 470 coal samples from the Straight Cliffs Formation, Kaiparowits Plateau (solid lines) with 218 coal samples from the Blackhawk Formation, Wasatch Plateau (dashed lines). Data used for the comparison are for coal core samples corresponding to intervals more than 5 feet thick: A) comparison of sulfur content, and B) comparison of calorific value.



Environmental Protection Agency (EPA) standard for sulfur dioxide (less than 1.2 lbs SO₂ per million gross Btu); 81 percent of the coal samples from the Wasatch Plateau meet the EPA compliance guideline. Although informative, it is important to note that this comparison is not an accurate comparison because of nonuniform sample distributions within the Kaiparowits and Wasatch Plateaus. Additional work is required for a valid comparison of in-ground coal quality abundances.

Conclusions

The rank of coal in the Straight Cliffs Formation of the Kaiparowits Plateau increases in a regular pattern from subbituminous B in the north to high-volatile bituminous B in the south. This laterally uniform change of rank is consistent with maximum burial depth controlling the rank of these coals.

Sulfur content shows a slight regional increase to the northeast. Sulfur contents are typically low but variable. Proximity to the Western Interior Seaway during peat accumulation, with attendant syngenetic influxes of marine waters along embayments and infiltration during early diagenesis, is the main causative factor controlling the distribution of sulfur in these coals. The nonuniform regional increase of sulfur to the northeast, together with lower calorific values in this area, suggest that EPA noncompliance coal will be more common in the northern part of the Kaiparowits Plateau.

The notable lack of a regional trend for ash yield is attributed, in part, to the diverse origins and modes of occurrence of ash-forming constituents. However, difficulties associated with varied sampling strategies, especially where ambiguous seam boundaries and partings are encountered, have certainly confounded our attempts to depict the lateral variability of ash. Despite these difficulties, high-ash areas within the Christensen zone are interpreted to delineate approximate locations of temporally persistent rivers and channels. Thick, low-ash

intervals indicate the location of raised mires where clastic mineral input was restricted.

Since neither the sample locations, nor the coal resources, are uniformly distributed across the Kaiparowits Plateau, the data presented here are not representative of the in-ground coal. For example, although the samples exhibit a bimodal rank distribution (Figure 4C), it cannot be assumed that the in-ground coal is neatly divided into two such populations. Indeed, this bimodal distribution is more likely a consequence of northern and southern clusters of sample locations. Nonetheless, the available data do allow a qualitative evaluation of coal quality, delineation of regional trends, and explanation of these trends as a result of depositional and burial history.

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Oil Families in the Grand Staircase-Escalante National Monument, Utah

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ABSTRACT

■ When evaluating the petroleum potential of the Grand Staircase-Escalante National Monument, it is important to establish the number of oil types or families based on geochemical characteristics. Saturated hydrocarbon (sat HC), biological marker, and stable carbon isotope data were used to define at least two distinct oil families that occur in the area.

The first oil type has been found as live oil stains in the Cambrian Tapeats Sandstone in two exploratory oil wells drilled in the Monument. In the Burnett Federal 36-1 well, drilled east of Kanab (T. 34 S., R. 3 W., sec. 36), and in the BHP Federal 28-1 well, drilled near Capitol Reef (T. 33 S., R. 7 E., sec. 28), the Tapeats oil is characterized by a Pristane/Phytane (Pr/Ph) ratio greater than 1 (generally about 1.5), a relatively high ratio of diasteranes to regular steranes, and a relatively heavier isotope signature ($\delta^{13}\text{C}$ sat HC = -27.9 ± 0.2). The probable source of this oil type is the Precambrian Chuar Group rocks or possibly the Cambrian Bright Angel Shale. Dead oil shows in the Devonian Ouray Formation in the BHP Federal 28-1 well are compositionally similar to the Tapeats oils and, hence, may be part of the Cambrian-Precambrian oil family.

The second oil family is represented by the oil produced from the Upper Valley field (Permian Kaibab reservoir) and by heavy oils or tar sands in the Circle Cliffs area and immediate vicinity. Distinguishing features of this sulfur-rich oil type are Pr/Ph ratios commonly less than 1, low ratios of diasteranes to regular steranes, and relatively lighter isotope values ($\delta^{13}\text{C}$ sat HC = -30.1 ± 0.3). The specific source of these oils is unknown, but geochemical data suggest a marine carbonate or carbonate-evaporite source. Another possible source could be an algal-bacterial-rich marine shale, deposited under anoxic conditions, high in sulfur and organic matter, that generates oils not unlike carbonate-sourced oils. One such candidate is the Permian Phosphoria Formation or its stratigraphic equivalents.

A low gravity oil (14 degrees API) produced in the Upper Valley field from the Mississippian Redwall Limestone may be a third oil type, but characterization is not possible due to the unavailability of samples.



These data suggest that future energy resource estimates of the Monument should address at least two oil families or petroleum systems, but more geochemical data are necessary to confirm the identity of the effective source rocks. A better understanding of the petroleum systems is required to provide accurate resource assessments, which, in turn, will assist in the planning, development, and management of the Monument's petroleum resources.

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Petroleum Exploration in Environmentally Sensitive Areas: Applications for Noninvasive Geochemical and Remote Sensing Methods

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Surface indications of oil and gas seepage have been noted for thousands of years and such seeps have led to the discovery of many important oil-producing areas. The surface expression of hydrocarbon migration and seepage can take many forms, including:

- 1) anomalous hydrocarbon concentrations in the soil, sediment, water, and even atmosphere;
- 2) microbiological anomalies and the formation of "paraffin dirt";
- 3) mineralogical changes such as the formation of calcite, pyrite, uranium, elemental sulfur, and certain magnetic iron oxides and sulfides;
- 4) bleaching of red beds;
- 5) clay mineral changes;
- 6) electrochemical changes;
- 7) radiation anomalies;
- and 8) biogeochemical and geobotanical anomalies.

Bacteria and other microbes play a profound role in the oxidation of migrating hydrocarbons, and their activities are directly or indirectly

ABSTRACT

■ The petroleum potential of the Grand Staircase-Escalante National Monument (GSENM) may be great, but it remains undocumented. Surface geochemical and remote sensing methods can reliably detect and map the elevated hydrocarbon concentrations and hydrocarbon-induced changes commonly associated with oil and gas accumulations. Such anomalies are present over several southern Utah fields, including Upper Valley field. Remote sensing methods enable rapid, yet reliable, screening of large areas for the presence of hydrocarbon-induced alteration of soils and vegetation. Noninvasive surface geochemical methods such as soil gas and microbial methods can effectively provide ground-truths for remote sensing anomalies, as well as detect hydrocarbon microseepage where remote sensing methods may not be applicable. The results of such surveys of the GSENM can identify those areas with highest petroleum potential, thereby protecting the greater part of the Monument from more invasive exploration methods that would be focused on a small number of high potential areas.

responsible for many of the surface manifestations of hydrocarbon seepage. These activities, coupled with long-term migration of hydrocarbons, lead to the development of near-surface oxidation-reduction zones that favor the formation of a variety of hydrocarbon-induced chemical and mineralogical changes (Figure 1). This hydrocarbon-induced alteration is highly complex and its varied surface expressions have led to the development of an equally varied number of surface exploration techniques. These include soil gas and soil microbial methods, soil iodine and soil trace metal methods, soil carbonate methods, magnetic and electrical methods, radioactivity-based

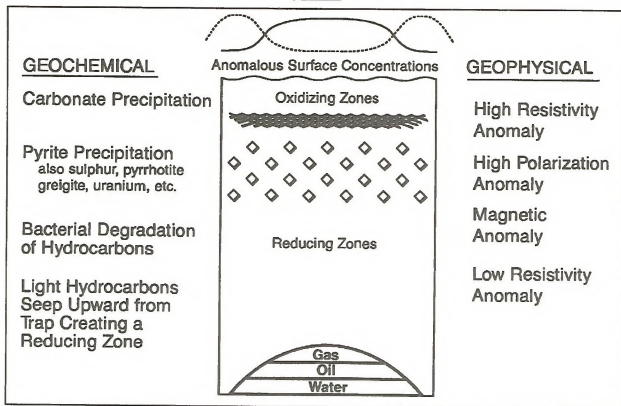


Figure 1. Generalized model of hydrocarbon-induced geochemical and geophysical alteration of soils and sediments (from Schumacher, 1996; reprinted with permission).

methods, and remote sensing methods. The formation of such anomalies and their implications for petroleum exploration are not the subject of this report; however, these topics are discussed in Matthews (1986), Klusman (1993), and Schumacher and Abrams (1996).

Surface Exploration Assumptions and Uncertainties

Basic Assumptions

The underlying assumption of all near-surface geochemical exploration techniques is that hydrocarbons are generated and/or trapped at depth and leak in varying but detectable quantities to the surface. This has long been shown to be an established fact, and the close association of surface geochemical anomalies

with faults and fractures is well known (Jones and Drozd, 1983; Horvitz, 1985; Price, 1986). It is further assumed, or at least implied, that the anomaly at the surface can be reliably related to a petroleum accumulation at depth. The success with which this can be related is greatest in areas of relatively simple geology and becomes increasingly difficult as the geology becomes more complex. The geochemical or microbial anomaly at the surface represents the end of a petroleum migration pathway, a pathway that can range from short-distance vertical migration at one end of the spectrum to long-distance lateral migration at the other extreme (Thrasher et al., 1996). Relationships between surface geochemical anomalies and subsurface accumulations can be complex; proper interpretation requires integration of seepage data with geological, geophysical, and hydrologic data. Understanding geology, and hence petroleum dynamics, is the key to using seepage data in exploration.



Macroseepage Versus Microseepage

The term *macroseepage* refers to visible oil and gas seeps—very localized areas containing large concentrations of light hydrocarbons as well as, if available, high molecular weight hydrocarbons. Macroseeps are localized at the termination of faults, fractures, and outcropping unconformities or carrier beds. It is these visible seeps that have led to the discovery of many of the world's important oil and gas producing areas (Link, 1952; Macgregor, 1993).

Microseepage is defined as high concentrations of analytically detectable light hydrocarbons in soils, sediments, or waters. These invisible seeps are recognized only by the presence of anomalous concentrations of light hydrocarbons (principally C_1 - C_3), hydrocarbon-oxidizing microbes, or hydrocarbon-induced alteration products. High molecular weight hydrocarbons may be present in ever-wet or intermittently wet environments; however, only light hydrocarbons are expected above the water table. Most surface geochemical methods, including both direct and indirect methods, are designed to detect microseepage.

The existence of microseepage is supported by a large body of empirical evidence (Price, 1986; Klusman, 1993; Klusman and Saeed, 1996). This includes: 1) increased concentration of light hydrocarbons and hydrocarbon-oxidizing microbes in soils and sediments above hydrocarbon reservoirs, 2) an increase in key light hydrocarbon ratios in soil gas over oil and gas reservoirs, 3) sharp lateral changes in these concentrations and ratios at the edges of the surface projections of these reservoirs, 4) similarity of stable carbon isotopic ratios for methane and other light hydrocarbons in soil gases to those found in underlying reservoirs, and 5) the disappearance and reappearance of soil gas and microbial anomalies in response to reservoir depletion and repressuring. Klusman and Saeed (1996) have shown that microseepage occurs by a vertical migration mechanism of displacing water by ascending gas bubbles—that is, the "buoyancy of microbubbles." Their

computer simulation of this mechanism yields results consistent with the observations noted above.

Anomaly Recognition

Hydrocarbon microseepage data, whether it is soil gas or microbial or other indirect measurements, is inherently noisy data and require adequate sample density to distinguish between anomalous and background areas. Matthews (1996) has reviewed the importance of sampling design and sampling density in target recognition, and states that undersampling is probably the major cause of ambiguity and interpretation failures involving surface geochemical studies. To optimize the recognition of an anomaly, the sampling pattern and sample number must take into consideration the objectives of the survey, the expected size and shape of the anomaly (or geologic target), the expected natural variation in surface measurements, and the probable signal-to-noise ratio (Matthews, 1996). Defining background values adequately is an essential part of anomaly recognition and delineation; Matthews suggests that as many as 80 percent of the samples collected should be obtained away from the prospect or feature of interest for which the hydrocarbon potential is being evaluated.

Oil and Gas in the Grand Staircase-Escalante National Monument

The potential petroleum resources of the Grand Staircase-Escalante National Monument may be considerable; however, this resource potential remains largely undocumented at this time. The present knowledge of mineral and energy resources of the GSENM has most recently been summarized in a report by the Utah Geological Survey (Allison, 1997).

The report notes that the Monument contains all the elements necessary for major oil and gas accumulations: source rocks, reservoirs, and



structural and stratigraphic trapping mechanisms. Commercial oil accumulations have been discovered both within and along the margins of the Monument at Upper Valley field and numerous oil shows are known from wells and outcrops (Peterson, 1973; Montgomery, 1984; Uphoff, 1997). The Upper Paleozoic-Triassic section is most prospective for heavy oil and tar sands; the Cambrian-upper Precambrian is most prospective for light oil and associated gas. Although the geologic characteristics of the Monument and the Kaiparowits basin as a whole are favorable for hydrocarbon generation and accumulation, too few exploratory wells have been drilled to properly evaluate its oil and gas potential. A thorough inventory of the Monument's natural resources, including the potential oil and gas accumulations, must be undertaken to develop a management strategy to most effectively utilize those resources.

Geochemical and Remote Sensing Methods

The surface and near-surface expression of hydrocarbon migration and seepage can take many forms, ranging from elevated hydrocarbon concentrations in soils to complex mineralogic, microbial, and botanical changes. These various surface manifestations have led to the development of an equally diverse number of exploration methods. Some are geochemical, some are geophysical, and some fall under the category of remote sensing.

Advances in surface exploration methods, coupled with an improved understanding of hydrocarbon migration processes, have led to an increased usage of various remote sensing and surface geochemical methods to detect and map the small but anomalous hydrocarbon concentrations, or hydrocarbon-induced changes, that occur above subsurface oil and gas accumulations. The noninvasive, low-impact nature of some of these techniques makes them ideally suited for use in an early stage evaluation of the petroleum potential of environmentally sensitive areas such as the GSENM.

In general, direct hydrocarbon detection methods, such as soil gas analysis, are preferable to indirect methods, such as iodine or soil alteration methods, or nonseismic geophysical methods. Although this is not the place to discuss the advantages and limitations of each of the many commercially available methods, it should be noted that of the many indirect geochemical methods, only the microbial method is uniquely associated with the presence of light hydrocarbons in soil. Other indirect methods, such as iodine or soil alteration anomalies or geobotanical anomalies, form in response to the reducing conditions (or redox boundary) often associated with strong hydrocarbon seepage; however, factors other than hydrocarbon seepage can produce similar reducing environments and, even if due to hydrocarbons, could result from biogenic methane and thus be unrelated to deep oil or gas potential (Schumacher, 1996).

Indirect effects that are detectable from satellite imagery or aeromagnetic data do, however, have an essential place in reconnaissance surveys of large and often inaccessible areas, such as the GSENM. For such regions, they represent cost-effective "first look" methods for locating soil or rock alteration anomalies, vegetation anomalies, and other changes that might result from hydrocarbon seepage. Such anomalies must ultimately be independently evaluated using soil gas and/or microbial methods in order to establish that the anomaly in question is in fact due to hydrocarbon seepage.

Direct Hydrocarbon Detection Methods

The analysis of hydrocarbons in soils and soil gases represents one of the earliest surface geochemical methods used, and one of the most researched and tested geochemical survey approaches (Horvitz, 1939, 1985; Stahl et al., 1981; Jones and Drozd, 1983; Klusman, 1993). Light hydrocarbons (i.e., low molecular weight hydrocarbons) can reside in soil and shallow sediments in a number of ways: 1) as free gas in the effective porosity, 2) as interstitial gas



that is occluded in the pore spaces between grains, and 3) as gas adsorbed onto the sedimentary particles or within carbonate cements. These different ways have led to the development of different techniques for sampling and analysis of soil hydrocarbons, some of which are described below:

- *Free soil gas, probe*—The probe method involves driving a 1/2-inch diameter rod into the ground to a depth of approximately 3 feet. A gas sample is removed from the hollow probe via a syringe and injected into an evacuated gas-tight container. Later, the sample is removed from the container and injected into a gas chromatograph and analyzed for methane, ethane, ethylene, propane, propylene, iso- and normal butane, and sometimes also for nonhydrocarbon gases. Since the soil is only slightly disturbed by the probe, the hydrocarbons measured are believed to be those primarily associated with the free gas in the subsurface. Advantages of the probe method are low cost, ability to access terrain not accessible by truck or all-terrain vehicle, and minimal environmental impact. Disadvantages may be low hydrocarbon concentrations, sensitivity to soil type and moisture, and daily or seasonal variations in concentration.
- *Free soil gas, augured hole*—A 2- to 4-inch-diameter hole is augured to a depth of 8 to 10 feet, the lower few inches of the hole are sealed from the atmosphere, and a gas sample is removed from the bottom of the hole into an evacuated sample container and stored until the sample is ready for analysis by gas chromatography. The collected gas sample is believed to contain both free and occluded gas, the latter having been liberated by disaggregation of the soil during auguring of the hole. The principal advantage of augured holes is that the greater depth of sampling ensures better quality samples, higher light hydrocarbon concentrations, and more reproducible results. Disadvantages are a somewhat higher cost and, depending on terrain, more limited access to the survey area.

An example of the results of a Utah soil gas survey using augured holes is shown in Figure 2. In the early 1980's, ARCO conducted several soil hydrocarbon surveys over the Iron Springs area in Iron County to assess the probability of hydrocarbon charge to the Three Peaks anticline. The anomalies from the soil gas survey show remarkable correlation with the anticline as mapped from seismic data; however, the center of the anomaly appears to be displaced several miles downdip from the crest of the anticline (Van Kooten, 1988). A well drilled at the crest of the anticline encountered only noncommercial quantities of oil in Permian and Triassic formations. The possibility that the hydrocarbon anomaly represents leakage from a hydrodynamically displaced oil accumulation, such as occurs at Upper Valley field, remains to be tested.

- *Canned headspace gas*—A specified volume of soil or sediment is collected from the bottom of an augured hole (or seismic shot-hole), placed in a can and covered with a measured volume of water or brine containing a bactericide, and sealed in the sample can. Gas is sampled from the headspace through a silicone septum on the top of the can. The can is shaken or sometimes heated prior to sampling to release the interstitial gases contained within the pore spaces of the sediment. Advantages of this method are ease of sample collection, shipping, and storage. Disadvantages are the same as those associated with augured holes.
- *Adsorbed gas*—Adsorbed gas is also referred to as acid-extracted gas, Horvitz adsorbed gas, sorbed gas, bound gas, or desorption gas. In this process, the coarse-grained fraction of the soil or sediment may be removed by wet-sieving a set volume of the bulk sample. The fine-grained portion, less than 63 microns, is heated in phosphoric acid in a partial vacuum to remove the bound hydrocarbons (Horvitz, 1985). The acid-extracted gas is analyzed for light hydrocarbons through pentane; hydrocarbons associated with the free gas phase are lost in the wet

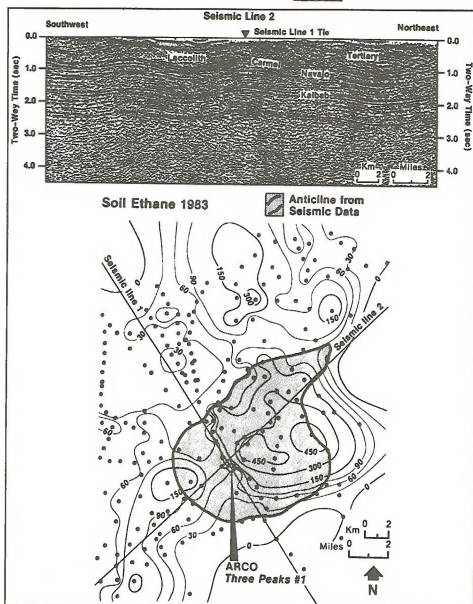


Figure 2. Upper figure is interpreted seismic line 2 showing Three Peaks anticline below laccolith. Lower figure is map showing ethane values (ppm) for soil gas survey of the area. Heavy line outlines structural closure beneath the Three Peaks anticline; sample locations are shown as solid circles. Note the close correspondence of the ethane anomaly with the anticline (modified from Van Kooten, 1988; reprinted with permission).

sieving procedure. Data generated by this method seem generally more reproducible and background noise levels much lower than for the previous methods discussed. Disadvantages include sensitivity to soil mineralogy and acidity, as well as a poor understanding of the "adsorption" process.

- **Integrative adsorption**—Acquisition of soil gas is accomplished using a sampler consisting of a ferromagnetic wire coated with activated

charcoal (or other adsorbant) and inserted into a glass tube (Klusman, 1993). The sampler is buried at a shallow depth for a period of up to several weeks. The charcoal gradually adsorbs gases migrating to the surface and reaches equilibrium with these soil gases during its resident period. After retrieval, analysis is performed by thermal desorption mass spectrometry over a mass range that includes hydrocarbons from C_2 to C_{17} . This method of sample acquisition eliminates the effects of short-term variation in hydrocarbon flux or related meteorological changes. Additionally, it provides a mass spectrometer "fingerprint" that can be compared to similar fingerprints from known accumulations or reservoirs.

Disadvantages are higher analytical and field costs; there is

also the possibility that the adsorbant may adsorb a variety of gases and compounds much more strongly than hydrocarbons, thereby making interpretation more difficult.

Geomicrobial Methods

Bacteria and other microbes found in soils and sediments above petroleum accumulations play a significant role in the destruction of migrating hydrocarbons. Their activities are



directly or indirectly responsible for the varied surface manifestations of hydrocarbon seepage. Hitzman (1961) and Davis (1956, 1967) have discussed in great detail the degradation of hydrocarbons by bacteria and have established the framework for microbial methods for oil and gas exploration. Although differing in detail, the various methods directly or indirectly measure the presence and concentration of hydrocarbon-oxidizing bacteria in soils. The most widely used method, the Microbial Oil Survey Technique (MOST), has been used successfully in diverse geologic and environmental settings throughout the world (Beghtel et al., 1987; Lopez et al., 1994). With MOST, microseepage is recognized by observing the concentration and distributions of hydrocarbon-oxidizing microbes in soil samples collected at a depth of 6 to 8 inches. There is a direct and positive relationship between the hydrocarbon concentrations in soils and these microbial populations. High microbial populations are therefore indicators of light hydrocarbon migration pathways and/or leakage from oil and gas accumulations. Advantages of the microbial method are low cost, ease of collection, access to terrain not accessible by truck or all-terrain vehicle, minimal environmental impact, and effectiveness in areas of thin soils where soil gas sampling is difficult. Limitations include low or variable microbial counts in wet or highly alkaline soils.

Biogeochemical and Geobotanical Methods

Hydrocarbon microseepage creates a chemically reducing zone in the soil column at depths shallower than would be expected in the absence of seepage. Such leakage stimulates the activity of hydrocarbon-oxidizing bacteria, which decreases soil oxygen concentration while increasing the concentration of CO_2 and organic acids. These changes can affect pH and Eh in soils, which in turn affects the solubilities of the trace elements and consequently their availability to plants. The lack of essential nutrients such as iron, copper, manganese, and zinc—or their presence in excessive concentrations—can lead to physiologic and morphologic

changes in plants and can alter their spectral reflectance (Rock, 1984).

Applying biogeochemical techniques, Donovan and Dalziel (1977) measured reduced iron and manganese in the leaves of pine and sagebrush that grew over the Recluse oil field in Wyoming and found that the Mn:Fe ratio was highest over the field. Similar results were reported from Bell Creek oil field in Montana by Dalziel and Donovan (1984) and Roeming and Donovan (1985). At Bell Creek, as in most areas studied, soil and plant geochemical data are inversely related, with low concentrations of metals in soils from under plants possessing high metal concentrations in their leaves. McCoy and Wullstein (1988) analyzed leaves of sagebrush and greasewood from Blackburn oil field in Nevada and reported a halo anomaly of high Mn:Fe ratios surrounding the productive part of the field. McCoy et al. (1989) revisited Blackburn field and determined that the spectral reflectance of sagebrush from the anomalous area was lower than that of sagebrush from background areas.

Klusman et al. (1992) compared the concentrations of 20 trace elements in plants growing over and near two oil fields: Eagle Springs field in Nevada and Cave Canyon field in Utah. Klusman theorized that alkaline soil elements such as calcium, strontium, and barium are less available to plants growing in microseepage environments, whereas the transition trace elements such as iron, manganese, and vanadium increase in availability due to their increased solubility in the seepage environment. Data from Eagle Springs field supported the expected relationship, but data from Cave Canyon did not. More recently, McCoy (1993) investigated soil geochemistry and vegetation in the vicinity of three Utah oil fields: Salt Wash and Blaze Canyon oil fields in Grand County and Upper Valley field in Garfield County. His preliminary data is encouraging for statistically classifying and mapping multi-element biogeochemical anomalies associated with hydrocarbon seepage.

There is no doubt that hydrocarbon microseepage can have a pronounced effect on



soils and vegetation, but the specific response is not consistent for different species and sites. In addition, factors such as bedrock geology, soil type, soil moisture, slope, and climate can have a more pronounced effect than that due to the presence of hydrocarbons (Rock, 1984; Klusman et al., 1992).

Magnetic Methods

The presence of magnetic anomalies over oil and gas fields has been known for several decades, but it is only in recent years that the phenomenon has been critically examined. Seepage from hydrocarbon traps and mature source rocks results in a pronounced reduction of the redox potential in near-surface sediments and soils, leading to the formation of magnetic ferrous iron oxides and sulfides and the destruction of ferric iron oxides (Machel and Burton, 1991; Machel, 1996).

Analysis of data from geologically and geographically diverse regions shows that: 1) authigenic magnetic minerals may occur in near-surface sediments above petroleum accumulations, 2) that this hydrocarbon-induced mineralization is detectable with low-level, high-resolution aeromagnetic data, and 3) the magnetic susceptibility analysis of well cuttings (and sometimes soils) confirms the existence of the aeromagnetic anomalies (Foote, 1996). The presence of aeromagnetic and shallow sedimentary magnetic anomalies in the vicinity of Lisbon Valley field in southeastern Utah has been documented by Foote (1996).

While shallow sedimentary magnetic anomalies appear to be associated with many petroleum accumulations and migration pathways, hydrocarbon-induced mineralization is but one of several possible causes for such anomalies. Gay and Hawley (1991) and Gay (1993) urge caution in interpretation of such anomalies and cite examples of false anomalies caused by cultural contamination, geologic structure, and syngenetic magnetic sources such as detrital magnetite and burned coal seams. The origin of such shallow magnetic anomalies may well be hydrocarbon-related, but hydrocarbons are

an indirect cause at best and not always the most probable cause (Schumacher, 1996).

Remote Sensing Methods

Satellite-based remote sensing of hydrocarbon-induced alteration holds great promise as a rapid, cost-effective means of detecting anomalous diagenetic changes in surface materials. Research in the vicinity of Patrick Draw, Lost River, and Lisbon Valley fields during the NASA-Geosat test case project (for summary, see Lang and Nadeau, 1985) demonstrates that Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) data can be used to detect three types of hydrocarbon-induced changes: 1) reduction of ferric iron (red bed bleaching), 2) conversion of mixed-layer clays and feldspar to kaolinite, and 3) anomalous spectral reflectance of vegetation. The potential for successful application of these remote sensing techniques is greatest in areas of sparse vegetation and susceptible surface clays and red beds.

The NASA-Geosat study documents a variety of hydrocarbon-induced effects on vegetation and soil over oil and gas fields and their recognition using remote sensing data. At Patrick Draw field in Wyoming, for example, the most pronounced anomaly observed was an area of stunted sagebrush and an associated tonal anomaly visible on Landsat imagery. The anomaly overlies the field's gas cap and occurs in a region of strong light hydrocarbon microseepage, as shown in Figure 3 (Lang et al., 1985; Richers et al., 1982, 1986). The geology and production history of the field show that the sagebrush anomaly results from the upward migration of injected gases and waters used to maintain reservoir pressures in the field (Arp, 1992). These gases and waters produced anoxic, low-Eh, high-pH, and high-salinity soils that are toxic to the overlying sagebrush (Lang et al., 1985; Arp, 1992).

Another prominent anomaly occurs over Lisbon Valley field in San Juan County, Utah. The geology and geochemical alterations associated with Lisbon Valley field have been

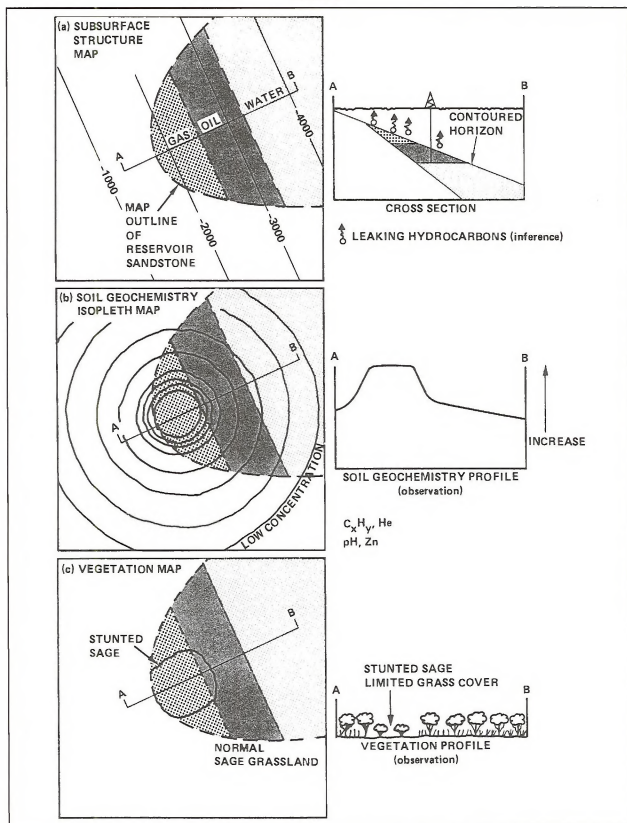


Figure 3. The empirical remote sensing exploration model for the Patrick Draw, Wyoming, NASA/Geosat test site. The stunted sagebrush anomaly coincides with soils characterized by high concentrations of light hydrocarbons, zinc, and elevated pH (from Lang and Nadeau, 1985; reprinted with permission).



described in considerable detail by Segal et al. (1984, 1986) and Conel and Alley (1985). They report that the distribution of the bleached outcrops of the Triassic Wingate Formation approximates the geographic limits of the oil and gas reservoirs at depth. The red color of the unbleached Wingate was found to result from a pervasive hematite-clay mixture coating virtually all sand grains, whereas the bleached Wingate appears white or gray due to the absence of these hematite coatings and the presence of kaolinite. The presence of bleached red beds above petroleum accumulations has also been reported from the Cement field area of Oklahoma, Garza field in West Texas, and several Wind River basin oil fields (Schumacher, 1996).

Implications for the Grand Staircase-Escalante National Monument

Numerous geochemical and geomicrobiological surveys and research studies have documented that hydrocarbon microseepage from oil and gas accumulations is common and widespread, is predominantly vertical (with obvious exceptions in some geologic settings), and is dynamic (Schumacher and Abrams, 1996). Because hydrocarbon microseepage is predominantly vertical, the extent of the anomaly at the surface can approximate the productive limits of the reservoirs at depth. These characteristics make surface geochemical exploration a valuable high-grading tool for rapid, cost-effective evaluation of the oil and gas potential of large areas.

The surface expression of hydrocarbon microseepage can be detected using any of a number of noninvasive methods, including satellite imagery, aeromagnetic data, and soil hydrocarbon and soil microbial surveys. Some of these methods detect hydrocarbons directly; others detect possible hydrocarbon-induced

changes in soils, rocks, and vegetation. A combination of remote sensing and ground-based microbial and soil gas surveys of the GSENM can identify those areas or structural features associated with strong hydrocarbon microseepage anomalies. These areas have the highest petroleum potential and can then be further evaluated using more invasive exploration techniques, such as seismic surveys and drilling, while leaving the larger portion of the Monument unaffected by petroleum exploration and production.

Summary and Conclusions

The potential petroleum resources of the Grand Staircase-Escalante National Monument could be considerable; however, this resource potential remains largely undocumented at this time. The Upper Paleozoic-Triassic section is most prospective for heavy oil and tar sands; the Cambrian-upper Precambrian is most prospective for light oil and associated gas. A thorough inventory of the Monument's natural resources, including its potential oil and gas accumulations, should be undertaken in order to develop a management strategy to most effectively utilize those resources.

Advances in surface exploration methods, coupled with an improved understanding of hydrocarbon migration processes, have led to the development of various remote sensing and surface geochemical methods to detect and map the small but anomalous hydrocarbon concentrations, or hydrocarbon-induced changes, that occur above oil and gas accumulations. The surface expressions of hydrocarbon seepage can take many forms, including:

- 1) anomalous hydrocarbon concentrations in soils and sediments;
- 2) microbiological anomalies;
- 3) mineralogic changes such as the formation of calcite, pyrite, uranium, elemental sulfur, and certain magnetic iron oxides and sulfides;
- 4) bleaching of red beds;
- 5) clay mineral changes;
- 6) acoustic anomalies;
- 7) electrochemical



- changes; 8) radiation anomalies; and
9) biogeochemical and geobotanical anomalies.

In southern Utah, surface geochemical anomalies and/or remote sensing anomalies have been documented over a number of petroleum accumulations and prospects including Upper Valley field, Kachina field, Lisbon Valley field, and the Three Peaks anticline. Remote sensing methods enable rapid yet reliable screening of large areas for the presence of hydrocarbon-induced alteration on soils and vegetation. Noninvasive surface geochemical exploration methods such as soil gas and soil microbial surveys are effective for providing ground-truths for the remote sensing anomalies, as well as for detecting hydrocarbon-induced changes where remote sensing methods may not be applicable. The results of remote sensing and surface geochemical surveys of the Grand Staircase-Escalante National Monument would provide considerable insight into the oil and gas potential of this region and could identify those portions of the Monument with the greatest petroleum potential. Furthermore, the use of surface geochemical and remote sensing methods would protect the greater part of the Monument from more invasive exploration methods since their use would be focused on a small number of high-potential areas.

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Floods, Ground-Water Levels, and Arroyo Formation on the Escalante River, South-Central Utah

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ABSTRACT

■ Upper Valley Creek on the Escalante River developed arroyos about 2 ka, 1.5 ka, 1 ka, and 0.5 ka, as well as historically. Arroyo dimensions preserved in the proximal alluvial fill indicate that the historic arroyo has the largest cross-sectional area of all late Holocene channels. On the distal margin of the floodplain at the confluence of Upper Valley and Birch Creeks, stratigraphy, snail species, and alluvial pollen indicate fluctuations in ground-water levels. Before 1.1 ka, sediments indicate consistently high ground water, pollen counts reflect changes in floodplain vegetation, and snails are mostly aquatic species. After 1.1 ka, the stratigraphy shows coarser units separated by evidence of surficial fires, the pollen record indicates an increase in woody species and high Cheno-Ams in the periods between arroyos, and snails indicate dry floodplains. Our results suggest that prehistoric arroyos may have been initiated during periods of low summer rainfall and that ground-water levels are not consistently related to arroyo incision.

Arroyo cutting, the downcutting of steep, vertical-walled channels by ephemeral streams, caused numerous environmental and economic problems in the American Southwest around the turn of the century. Many scientific explanations have been proposed to explain the timing and mechanics of arroyo cutting (Graf, 1983; Webb, 1985). For the arroyos that formed historically, Bailey (1935) reported overgrazing by cattle as the primary reason, citing the increased runoff that occurs on trampled, denuded land. Bryan (1925) linked arroyo cutting to a climatic shift toward drier conditions, causing decreases in ground-water levels that subsequently decreased the hydraulic roughness of floodplains. However, Bryan (1940) also believed cattle to be the triggering device for climatically induced downcutting in the most recent series of erosional events, as did Antevs (1952). For the Escalante River in south-

central Utah, Webb and Baker (1987) reported the association of unusually large floods with initiation of arroyos. As with previous researchers, they concluded that livestock grazing was secondary in importance to climatic change.

Arroyos formed before the 19th century in several well-documented periods of the late Holocene, during which domestic livestock were not present on the landscape. Most geomorphologists therefore attempt to link climatic change or fluctuations, or intrinsic geomorphic processes, to the initiation of arroyos, instead of solely blaming poor land-use practices (e.g., Hereford, 1986). Hack (1942) considered evidence of prehistoric arroyo cutting events and concluded that climatic changes, independent of human



activities, were responsible. Leopold (1976) and Hereford (1984) also concluded that periodic droughts were the primary factor controlling modern arroyo cuts. Boisson and Patton (1985), noting differences in the alluvial stratigraphy of neighboring washes in the Escalante drainage, concluded that input of sediment by landslides, apparently independent of climate, was the primary factor in aggradational and erosional cycles. For the Escalante River, Webb (1985) noted the synchronicity, in terms of radiocarbon dating, between periods of arroyo formation and periods during which large paleofloods occurred.

Even though climatic fluctuations are considered to be an important factor contributing to arroyo cutting in the southwestern United States, arroyos did not entrench simultaneously in the 19th or 20th centuries. Webb (1985) noted that downcutting in southern Utah spanned 50 years and did not correlate well with years of high or low annual precipitation (as recorded in tree-ring or instrumental records). Lack of close association reduces the probability that drought-induced lowering of alluvial aquifers was fundamental to arroyo incision, as first suggested by Bryan (1925). However, with the relatively low resolution of radiocarbon dating, prehistoric arroyo incision appears reasonably synchronous, but not with periods of drought. Therefore, broader scale climatic fluctuations or long-term changes in floodplain environments may better explain the phenomenon of arroyo initiation.

In order to examine long-term trends in climate related to arroyo initiation, we assembled a record of late Holocene arroyo formation for Upper Valley Creek (Figure 1). Our research is an extension of the work of Webb (1985). To test the hypothesis that fluctuations in ground-water levels may contribute to arroyo

initiation, we interpreted changes in the floodplain environment on the margin of Upper Valley Creek (Figure 2). For one well-dated section of alluvial stratigraphy, we analyzed the physical stratigraphy, fossil pollen, and fossil mollusks to determine the relation between ground-water levels and the formation of arroyos. We also examined possible causes and rates of arroyo filling.

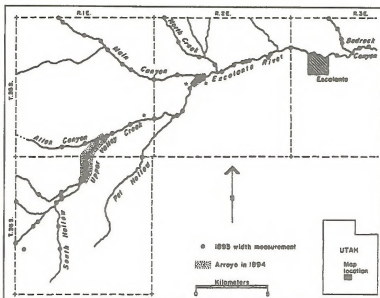


Figure 1. Map of the drainage of Upper Valley Creek, south-central Utah. The 1893 width measurements were made by the General Land Office (Webb, 1985). Asterisks indicate the locations of stratigraphic sections reported in this paper.

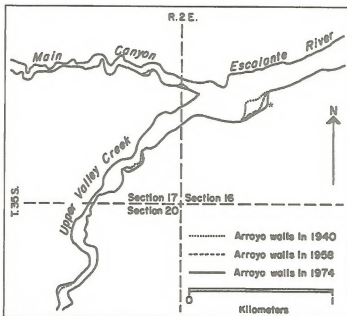


Figure 2. Map of the confluence of Main Canyon and Upper Valley Creek showing the location of the distal floodplain stratigraphic section at kilometer 20 (*).



Background

Gregory and Moore (1931) report that flow in the Escalante River increased fourfold after 1882, suggesting that ground-water levels were high just before arroyos became incised in the region (1882-1909). The current incised channel of Upper Valley Creek formed during a period of unusually large floods between 1909 and 1932 (Webb and Baker, 1987). The discharges of some of these floods approach the envelope curve of largest floods recorded on the Colorado Plateau (Webb, 1985). These floods occurred during a period of anomalous and above-average precipitation in the region, but they also coincided with a peak in live-stock numbers and the growing population of Escalante. The cross-sectional area of the channel in the mid-1980's was considerably larger than the channel observed by surveyors in the 19th century (Figure 3). Arroyo dimensions preserved in the proximal alluvial fill (e.g., Figures 4 and 5) indicate that the historical arroyo has the largest cross-sectional area of all late Holocene channels. The magnitude of change on Upper Valley Creek is similar to the change on Kanab Creek, which incised in 1882-83 (Smith, 1990, Webb et al., 1991). Webb (1985) concluded that, in addition to the historical arroyo, Upper Valley Creek developed arroyos about 2 ka, 1.5 ka, 1 ka,

and 0.5 ka. These dates are in general accord with the regional chronology proposed by Hereford et al. (1996) and the dates for large floods on the Escalante River downstream (Webb et al., 1988).

Methods

Dating of Arroyo Stratigraphy

Stratigraphy at several places along Upper Valley Creek was described and ^{14}C dated initially by Webb (1985). Subsequently, additional sections were described and new ^{14}C dates were obtained. Most of the ^{14}C dates are from charcoal clustered in the stratigraphy in specific zones or layers, although some litter-fall layers or disseminated fine-grained organics were also dated. Other characteristics of the stratigraphy were described, including the particle-size distribution of individual layers, the presence of oxidized zones and ash indicative of surficial burns, gleying and mottling of sediments indicative of anoxic conditions and high ground-water levels, and traceable contacts that describe channel dimensions.

At the confluence of Upper Valley Creek and Main Canyon (kilometer 22), floods from

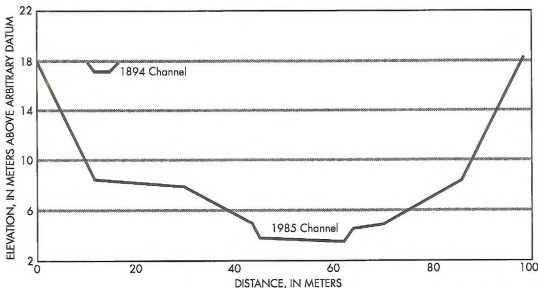


Figure 3. Cross sections of the channel of Upper Valley Creek at the section-line crossing between sections 4 and 9 of T. 36 S., R. 1 E. The dimensions of the channel identified in the 1893-94 General Land Office survey were measured from a remnant still present at the site.



Main Canyon have eroded an arcuate-shaped exposure into the distal margin of the floodplain (Figure 2). Webb (1987) analyzed historical aerial photographs and found that this site was one of the few places along Upper Valley Creek where the arroyo walls had changed after 1940, thereby leading to fresh exposures of the alluvial stratigraphy. Initially described by Webb (1985), this section is well-dated with five ^{14}C dates (Figure 6), all from charcoal either from within specific zones or associated with surface burns. About 40 m away, we described a similar section and collected sediment samples for analysis of preserved pollen. We correlated the two sections by tracing burn horizons from one section to the other. The top of this column (0.0 m) is assigned a date of 50 years B.P. because it was the floodplain until 1909.

Pollen

Analysis and interpretation of alluvial pollen is problematic. Fall (1987) showed pollen to be an unreliable indicator of both regional and local vegetation in Chaco Canyon. Buoyant pollen grains like *Pinus* (pine) and Gramineae (grass) settled out with silt and clay while denser grains like the Chen-Ams (undifferentiated pollen from the family Chenopodiaceae and the genus *Amaranthus*) and *Artemisia* (sagebrush) settled with sand and gravel (Fall,

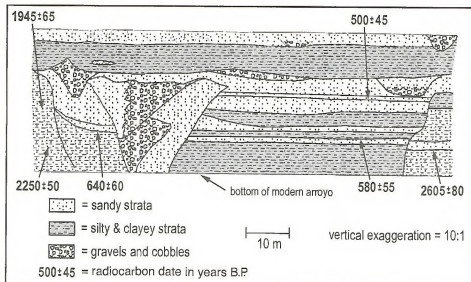


Figure 4. Cross section of stratigraphy preserved at kilometer 14 on Upper Valley Creek.

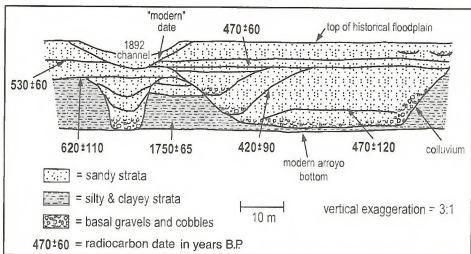


Figure 5. Cross section of stratigraphy preserved at kilometer 20 on Upper Valley Creek (modified from Webb, 1985).

1987). Therefore, choice of study area is critical to any objective interpretation of floodplain environment using alluvial pollen.

We chose to sample the section at kilometer 22 specifically to reduce the bias resulting from size and density sorting of alluvial pollen. This section represents the distal margin of the floodplain where the sorting associated with higher energy depositional sites in the center of the floodplain is reduced. The physical stratigraphy also indicates high ground-water levels at various times, which suggests the possibility that pollen produced locally would be trapped in a marshy environment with minimal transport into the site during floods. To further

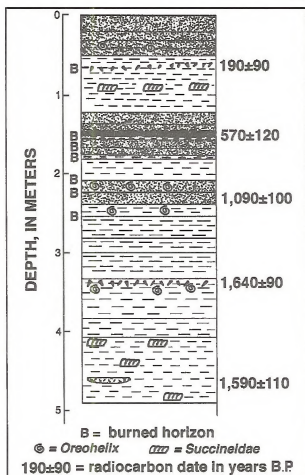


Figure 6. Cross section of stratigraphy preserved at kilometer 22 on Upper Valley Creek at the confluence with Main Canyon (modified from Webb, 1985). Solid black indicates clay strata, dashed lines indicate clayey silt strata, and fine stippling indicates sandy strata.

check the validity of our results, we examined the effect of particle size on pollen concentrations in a manner similar to Fall (1987).

Samples were collected every 20 to 60 cm in the stratigraphic section. Charcoal horizons were designated, and the locations of fossil mollusk shells were measured. To calibrate the modern pollen rain with that preserved in the stratigraphy, we collected samples of moss polsters from the general area. A polster is a living patch of moss that serves as an air filter, trapping and preserving airborne pollen (Moore et al., 1991). Sediment samples of 20-cm³ size and 2-cm³ polster samples were combined with a known amount of exotic-tracer spores (*Lycopodium*) to quantify pollen concentrations. Samples were treated with 10 percent hydrogen chloride (HCl), 49 percent hydrogen fluoride

(HF), and acetic anhydride with 10 percent sulfuric acid to remove carbonates, silicates, and organic matter (Faegri and Iverson, 1989). Sediment samples were also passed through a zinc bromide solution (specific gravity of 2.0) to float the pollen away from any remaining silicates (Pearsall, 1989). All samples were then stained with safranin, dehydrated with ethanol and t-butyl alcohol, and suspended in silicone oil. The resulting suspensions were mounted on glass slides and counted under a binocular microscope at 400x magnification. Pollen grains were tallied along parallel transects until a minimum of 300 terrestrial grains (including degraded grains and unknowns) had been counted. Pollen was identified by keys in Kapp (1969) and Moore et al. (1991) and by comparison to the pollen reference collection in the Laboratory of Paleocology of Northern Arizona University.

Results

Dates of Late Holocene Arroyos

The dates of prehistoric, late Holocene initiation of arroyos cannot be accurately determined using any means. Periods of erosion, such as times when arroyos were incised, can only be bracketed by ¹⁴C dating. This introduces considerable uncertainty into correlations of channels between discontinuous sections of stratigraphy, such as between the proximal and distal alluvial stratigraphy.

In accord with Webb (1985), we found that Upper Valley Creek developed arroyos about 2 ka, 1.5 ka, 1 ka, and 0.5 ka. Examples of dated stratigraphic sections appear in Figures 4 and 5. The accuracy of the initiation dates is low because the standard deviations of the ¹⁴C dates typically are ±60-120 years and the bracketing layers only approach the actual date of incision. One of the best examples of bracketing is at kilometer 20, where dates of 530±60 and 470±120 years B.P. bracket the erosion (Figure 5). Therefore, the dates of arroyo initiation in Upper Valley Creek have



a more realistic uncertainty of several hundred years. Addition of radiocarbon dates to the work first reported by Webb (1985) did not significantly change his conclusions.

Periods of filling, however, may be accurately dated. Once again at kilometer 20, three ^{14}C dates document the filling of an arroyo that became entrenched about 0.5 ka. The three dates— 470 ± 120 , 420 ± 90 , and 470 ± 60 years B.P.—indicate the arroyo filled very quickly with relatively well-sorted sandy sediments. At least three gravel lenses suggest the filling was not continuous, but instead, lingered at one level for an indeterminate, but likely short, period. We could not replicate this dating of filling episodes at any other section owing to the sparse distribution of organic material preserved in the stratigraphy.

Distal Floodplain Stratigraphy

At the confluence of Upper Valley Creek and Main Canyon, we described and dated parts of a 150-m section of alluvial stratigraphy on the distal margin of the floodplain (Figure 6). Five ^{14}C dates provide excellent resolution in this 5-m section within the last 1.6 ka. Our interpretation of the depositional environment indicates that the floodplain shifted between wet, marshy conditions and a dry environment several times during this period.

Below about 2.3 m in the stratigraphic section (older than 1.1 ka), sediments are mostly clayey silts with scattered stringers of gravel. The sediments are well-consolidated and mottled with orange (iron) and dark brown (manganese) staining, reflecting paludal (marshy) conditions. In local areas, slight gleying indicates at least temporary anoxic conditions associated with consistently high ground-water levels. A line of charcoal at about 3.3 m depth indicates a possible burned surface, but other signs of surface burning, such as ash or oxidized sediments, were missing. If this charcoal line resulted from burning of a dry floodplain, it would suggest that a consistently marshy floodplain dried out sufficiently to burn at about the time of the 1.6 ka arroyo cutting.

Above about 2.5 m, six burned horizons are prominent in the stratigraphy, providing a basis for correlation along the section. Most of these burned horizons are on the surface of laminated beds of silty fine sand, which indicates dry floodplain conditions. Significantly, a clay bed appears at 1.5 m depth with a ^{14}C date of 570 ± 120 years B.P., or just preceding the initiation of the 0.5 ka arroyo. This bed suggests a possibility of high ground-water conditions just before initiation of the arroyo. Between 1.2 and 0.5 m depth, strata of clayey silt indicate consistently wet floodplain conditions until a surface burn at 190 ± 90 years B.P., whereupon the stratigraphy is consistently sandy before onset of historical arroyo cutting.

Mollusks

Fossil mollusk shells were observed embedded in the stratigraphy of the distal margin of the floodplain. Shells from the terrestrial snail genus *Oreohelix*, a very common land snail in the Southwest (Bequaert and Miller, 1973), were removed from the stratigraphic column at 0.5, 2.2, 2.6, and 3.5 m (Figure 6). Shells from the Succineidae family of aquatic snails were found at 0.9, 4.2, 4.4, and 4.8 m. Succinids, which cannot be identified below family level with shells alone (Bequaert and Miller, 1973), require a moist habitat, which could even be shallow, open water. The presence of these fossil mollusks is consistent with the physical interpretation of the stratigraphy, indicating fluctuations in ground-water levels during deposition on the floodplain.

Alluvial Pollen

Pollen from moss polsters suggests consistent, although small, changes with distance from the floodplain. Polster 1 was gathered from a marsh on the current floodplain, 10 m from the base of the cutbank where sediments were gathered for the pollen profile section; grasses, sedges, and forbs dominate the plant community. Polster 2 came from the top of the cutbank, a dry environment where *Sarcobatus*, *Artemisia*, and *Cheno-Ams* (undifferentiated *Chenopodiaceae-Amaranthus*) predominate. Polster 3 was 20 m back from the top of the



modern arroyo, where pinyon-juniper woodland has taken over the old floodplain. Polster 4 was on a slickrock bench, in open pinyon-juniper woodland, 30 m above and 150 m away from Upper Valley Creek. The pollen concentrations of high-spine composites were highest in the marshy environment, woody shrubs and Cheno-Ams were highest on the dry floodplain, and *Pinus* and Cupressaceae were highest in the pinyon-juniper woodland.

The results of our analyses of alluvial pollen from all sediment sizes in the distal floodplain stratigraphy are shown in Figure 7 (the data are presented in Table 1). Concentrations of *Pinus* pollen, which indicate regional vegetation since pines are wind-pollinated and produce abundant pollen, are

reasonably constant, ranging between 45 and 65 percent of the total pollen concentration except at the 4.6 m depth where it was overwhelmed by Cheno-Am pollen. Except for a large peak at 4.2 to 4.6 m, the concentration

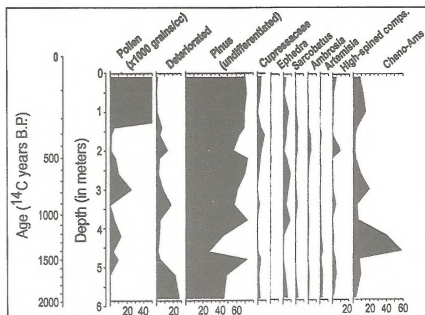


Figure 7. Pollen concentrations in the alluvial stratigraphy at kilometer 22 on Upper Valley Creek. The results are for all sediment sizes.

Table 1. Pollen data for the distal floodplain stratigraphy at the confluence of Upper Valley Creek and Main Canyon.

Sample depth (m)	0.1	0.5	1.0	1.4	1.6	2.0	2.2	2.6	3.0	3.4	3.8	4.2	4.6	5.2	5.8
Pollen concentration (10 ³ /cm ³)	66.3	72.2	149.0	5.1	1.9	1.8	7.1	10.4	25.7	0.6	5.9	13.4	4.3	0.8	1.1
Approximate age (ka)	0.06	0.11	0.17	0.25	0.32	0.44	0.51	0.64	0.78	0.92	1.06	1.23	1.41	1.50	1.69
POLLEN TYPE		POLLEN PERCENTAGE													
Deteriorated	2.30	1.20	1.80	7.32	5.00	14.24	4.43	3.38	8.39	18.30	5.10	4.47	2.78	22.96	27.81
Unknown	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.28	0.00	0.00	0.00	0.00	0.51	0.00	0.00
<i>Picea</i>	0.00	0.00	0.00	0.00	0.00	0.62	0.00	0.00	0.31	0.00	0.00	0.28	0.00	0.00	0.00
<i>Pinus</i> , undifferentiated	70.90	72.60	70.10	69.82	63.75	56.97	74.05	70.42	61.80	58.04	73.65	44.69	28.03	48.64	45.31
Cupressaceae	5.20	4.40	1.20	4.88	9.38	5.57	4.43	2.54	0.31	3.47	0.57	0.84	1.26	2.11	3.44
<i>Quercus</i>	0.90	0.00	0.60	1.83	2.81	0.62	1.90	0.56	0.00	1.58	0.85	0.28	0.51	1.21	3.44
<i>Ephedra</i>	0.90	0.60	0.30	1.22	1.25	0.00	1.27	0.28	0.00	0.32	0.57	0.84	0.00	0.00	0.31
Rosaceae	0.00	3.40	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.94
<i>Sarcobatus</i>	4.10	1.60	6.90	4.27	4.38	1.55	5.06	9.30	6.52	4.10	8.78	1.40	0.76	3.32	5.94
<i>Ambrosia</i>	0.60	0.60	1.20	3.35	2.50	2.79	1.58	0.56	0.93	2.84	0.85	0.84	0.76	0.91	3.44
<i>Artemisia</i>	0.30	0.30	0.90	0.91	3.75	4.33	2.53	1.13	0.62	0.95	1.70	1.40	1.01	2.11	1.25
High-spined composites	1.20	0.90	0.30	0.30	1.88	0.00	0.63	1.41	0.00	0.63	1.42	1.68	3.54	3.63	2.81
<i>Gramineae</i>	4.90	1.60	1.20	0.61	0.63	10.53	0.00	0.56	0.93	4.42	0.00	1.68	1.26	5.14	1.56
Cheno-Ams	8.70	12.50	15.40	5.18	3.13	2.79	3.80	9.58	20.19	5.36	6.52	41.34	59.60	9.97	3.75
cf <i>Fendlera</i>	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Onagraceae	0.00	0.00	0.00	0.00	0.63	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cf <i>Verbena</i>	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Betula</i>	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00
Cyperaceae	0.31	0.00	0.00	0.00	0.94	0.62	0.00	0.00	0.00	0.95	0.00	0.00	0.00	1.51	0.00
Terrestrial percentage	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Aquatic percentage	0.31	0.0	0.0	0.0	0.94	0.62	0.0	0.0	0.0	0.95	0.0	0.0	0.0	1.81	0.0



of Cheno-Am pollen ranges between 5 and 20 percent, whereas *Sarcobatus* (greasewood) typically contributes 2 to 10 percent.

Aggregates of Cheno-Ams and (or) *Sarcobatus* were found at almost every level below 2.6 m. Aggregates are clumps of pollen grains that adhere together and generally indicate that a flower was deposited in the sediment at that location (Pearsall, 1989), suggesting a local source. Pollen from *Ambrosia* (ragweed), *Artemisia* (sagebrush), and high-spined composites (a subgroup of Asteraceae that includes sunflowers) were present in low numbers at most levels.

The pollen profiles indicate potential environmental changes that are linked to arroyo processes. Periods between the known dates of arroyo cutting (e.g., 1.6 ka to 1.0 ka) generally have high concentrations of Cheno-Am pollen. This suggests that summer rainfall may have been higher during the periods when arroyos filled and floodplains aggraded. *Sarcobatus* pollen levels generally are higher in the periods between arroyos, particularly after 1.0 ka, which may suggest generally dry floodplain conditions. High-spined composites, which may indicate high ground-water levels on the basis of our polsters, are highest at about the times when arroyos were present. This suggests the possibility that concentration of ground-water outflow and runoff in a narrow, entrenched channel may enhance this type of riparian vegetation, not generally high ground-water levels on floodplains.

Discussion and Conclusions

Our work on Upper Valley Creek suggests that the relation between ground-water levels and arroyo initiation are not consistent through the record. Historical reports indicate that surface-water discharge increased, not decreased, before arroyos formed, suggesting that high water levels were present when arroyos were initiated. This is contrary to other observations that ground-water tables lowered before

arroyo initiation (Bryan, 1925). Our interpretation of the depositional environment on the floodplain, based on three different methods, consistently indicates that certain intervals between arroyos had high ground-water levels and that the dry floodplain, created by arroyo cutting and draining of the alluvial aquifer, has a signature in the stratigraphy. The results include a tantalizing pattern from one stratigraphic section that suggests that ground-water levels were high in several of the intervals between arroyos, but the relation is not consistent for all arroyos.

Our analyses of alluvial pollen are consistent with the interpretation of the physical stratigraphy and the types of fossil mollusks recovered. Despite this, the problems with alluvial pollen demonstrated by Fall (1987) are also evident in our analyses. For example, concentrations of grass pollen in whole sediment samples (Table 1) have a compelling, but deceptive, cyclical pattern that suggests high and low ground-water levels. High concentrations of grass pollen are associated with high levels of deteriorated grains, low overall pollen concentrations, and coarser strata. These possibly indicate reworking and secondary deposition that may affect concentrations of other pollen types.

Because of possible reworking, the pollen data are shown in Figure 8 without the data for strata at 1.6, 2.0, 3.4, 5.2, and 5.8 m. In addition, we adjusted the concentrations in Figure 8 by counting each aggregate as a single occurrence rather than tallying every grain, and indicating which levels contained aggregates. The new pollen profile is more subdued than the profile derived from all sediment sizes; however, the data contained in Figure 8 better represent the pollen signal from local sources, as opposed to pollen transported during floods. We tentatively conclude that our selection of a distal floodplain site may have alleviated some of the difficulties noted by Fall (1987) in using alluvial pollen to reconstruct floodplain environments. None of the strata we analyzed contain the sort of pollen assemblage that might be expected from reworked deposits (Fall, 1987). Fall (1987) found pine and grass pollen were preferentially deposited in clay-

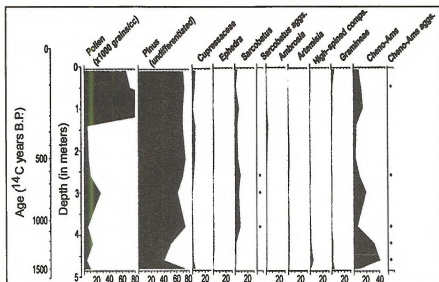


Figure 8. Pollen concentrations in fine-grained sediments extracted from the alluvial stratigraphy at kilometer 22 on Upper Valley Creek.

and silt-rich strata and *Ambrosia*, *Artemisia*, and Cheno-Am pollen were concentrated in sandy-gravel sediments (where Cheno-Ams clearly outnumbered *Pinus*). In contrast, our profile contains (poorly sorted) sandy sediments where *Pinus* pollen predominates and concentrations of grass pollen fluctuate in phase with Cheno-Ams. It would appear that marginal floodplain regions such as this receive a larger pollen component from local slope wash and pollen rain than they do from reworked alluvial deposition.

The pollen profiles shown in Figures 7 and 8 show some interesting trends that suggest other environmental changes besides fluctuations in ground-water levels. Pine pollen is produced in abundance in nearby forests and is widely dispersed by wind, resulting in high background levels as seen here. Since pine pollen is a fairly constant regional signal, it is important to this reconstruction as an indicator of both wetter periods, when annual plants produce abundant pollen, diluting the pine signal, and dry periods, when pine percentage increases relative to pollen input from annuals. Increased pollen production by annuals and lower pine concentrations are apparent in strata dated at about 1.2 and 0.8 ka, indicating moister periods. Drier overall conditions are evident around 1.0 and 0.5 ka, when arroyo cutting occurred, and may have been returning

when deposition was terminated by the latest episode of arroyo cutting.

The *Ephedra* pollen identified from Upper Valley Creek is the *E. nevadensis* type that Martin (1963) identifies as an indicator of winter precipitation. Similarly, *Artemisia* is more common in regions where winter precipitation dominates and Mehringer (1965) considered it an indicator of drier conditions in the Mojave Desert. Both *Ephedra* and *Artemisia* pollen in this profile

indicate a trend toward dominance of winter precipitation, and perhaps a weakening of the summer monsoon pattern, around 1.3 and 0.2-0.6 ka. High-spined composites and Cheno-Ams are both indicators of summer precipitation (Hevly, 1964), as is the Gramineae (Mehringer, 1965). High-spine composites, Cheno-Ams, and grass pollen all indicate that summer precipitation in Upper Valley Creek was most abundant from 1.2 to 1.5 and 0.7 to 0.8 ka, or periods when arroyos filled and floodplains were aggrading.

Our reconstruction of floodplain environments on Upper Valley Creek encompasses arroyo-cutting episodes that occurred around 1.6, 1.0, and 0.5 ka (Webb, 1985). All three episodes coincide with periods when the pollen data indicate a decrease in the summer component of the regional rainfall. However, Webb (1985) noted that most floods on the Escalante River occur during August, the peak of the summer monsoon period. This would seem to indicate that major arroyo-cutting floods are more likely to occur during years of a weak monsoon pattern, when ground cover plants are sparser and any summer storm that does develop will result in more (and faster) runoff. Increases in summer precipitation between periods of arroyo formation might suggest that local summer thunderstorms transport high concentration runoff onto the floodplain, depositing sediment



and filling channels. Therefore, the phenomenon of cutting and filling of arroyos in Upper Valley Creek may best be explained by fluctuations in seasonality of precipitation, not in changes in ground-water levels.

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Surficial Geology and Geomorphic Processes in the Grand Staircase-Escalante National Monument Area, Utah

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The distinctive scenic qualities of the Grand Staircase-Escalante National Monument area are a reflection of the great variety of geologic materials and of natural geomorphic processes that have shaped the land. Careful management of the scenic, recreational, wildlife, botanical, and scientific resources requires an understanding of the distribution of materials, natural process equilibrium, and zones affected by potentially hazardous processes.

ABSTRACT

■ The distinctive scenic qualities of the Grand Staircase-Escalante National Monument area reflect the variety of geologic materials and geomorphic processes that have shaped the land. Management of the scenic, recreational, wildlife, botanical, and scientific resources requires understanding of the distribution of materials, natural process equilibrium, and zones affected by potentially hazardous processes. Extensive data on deposits and processes was compiled by the U.S. Geological Survey in the early 1980's in anticipation of development of coal resources of the Kaiparowits Plateau, and much of the data was published in an environmental geology folio (Miscellaneous Investigations Maps I-1033 A to L). The volumes on bedrock geology (Sargent and Hansen, 1980b), surficial geology (Williams, 1985), geology-related scenic features (Carter and Sargent, 1983), landforms (Sargent and Hansen, 1980a), geologic cross sections (Lidke and Sargent, 1982), and ground-water availability (Price, 1977b) are especially relevant to management and interpretation of the National Monument.

Surficial deposits include all geologic materials within 1 meter of the surface and the total thickness of unconsolidated sediment. Fifty types of surficial deposits were mapped at 1:125,000 across a 1-degree-square area covering most of the Monument. The rest of the Monument area in Utah was covered by the preliminary geologic map of the Kanab 1:100,000 scale quadrangle (Sable and Hereford, 1990). Subdivision of surficial deposits is based on differences in mode of deposition, lithologic composition, and age. Mode of deposition indicates dominant geomorphic processes that affected various parts of the Monument in the past and may pose hazards in the future. Lithologic composition affects the chemistry, texture, and erodibility of soils formed on the deposits, and thus controls plant distribution and landscape stability. The ages of episodes of deposition provide clues about the probability that hazardous processes, such as the giant landslides and debris flows of the past, will recur over a given span of time.



The U.S. Geological Survey (USGS) has been intensely studying the area of the Grand Staircase-Escalante National Monument for over 35 years and has produced a great number of maps and reports primarily focused on evaluating the coal resources of the Kaiparowits Plateau and preparing for environmental impacts of coal extraction. The area is covered by mapping at scales of 1:250,000, 1:125,000, 1:100,000, 1:62,500 and 1:24,000. Over twenty five 1:24,000-scale, 7.5-minute geologic quadrangle maps have been published (some by the Utah Geological Survey in cooperation with the USGS). From the late 1970's to the mid-1980's Ken Sargent led the Kaiparowits Environmental Geology Project in an effort to map and synthesize available data into a USGS Bulletin (Sargent, 1984) and a 12-volume folio of maps at 1:125,000 scale that was eventually published as USGS Miscellaneous Investigation Maps I-1033 A to L. That project covered a 1-degree-square area centered on the Kaiparowits Plateau corresponding to the combined Escalante and Smoky Mountain 1-degree by 30-minute quadrangles. The maps included all the area of the National Monument except for the westernmost part, which was subsequently covered by the 1:100,000-scale geologic map of the Kanab quadrangle (Sable and Hereford, 1990).

Two maps of the folio concerned bedrock geology, three concerned themes related to geomorphology and surficial deposits, two concerned coal resources, two concerned ground water, two concerned surface water, and one concerned geologic features of scenic interest. The maps are as follows:

1033-A:
Chemical Quality
of Ground WaterPrice, 1977a

1033-B:
Availability of
Ground WaterPrice, 1977b

1033-C:
Extent and
Thickness of CoalHansen, 1978a

1033-D:
Overburden on
Major Coal ZonesHansen, 1978b

1033-E:
Surface Water
Streamflow, etc.Price, 1978a

1033-F:
Chemical Quality
of Surface WaterPrice, 1978b

1033-G:
LandformsSargent & Hansen, 1980a

1033-H:
Areas of
LandslidingFuller et al., 1981

1033-I:
Bedrock GeologySargent & Hansen, 1980b

1033-J:
Cross SectionsLidke & Sargent, 1982

1033-K:
Geology-Related
Scenic Features.....Carter & Sargent, 1983

1033-L:
Surficial Geology.....Williams, 1985

Work on many of these topics has continued, and at this symposium we have heard updates on ground water from Geoff Freethy of USGS, on coal resources from Robert Hettinger and Mark Kirschbaum of USGS, on geologic map compilation from Grant Willis of Utah Geological Survey, on landslides and other hazards from Kimm Harty and Janine Jarva of Utah Geological Survey, and on geomorphology from Richard Hereford and Robert Webb of USGS. The wealth of geologic data in the I-1033 and subsequent studies is vitally important to management and interpretation of the National Monument.

Map of Geology-Related Scenic Features

The map of geology-related scenic features (Carter and Sargent, 1983) is particularly use-



ful as an interpretive resource for visitors to the park because it was originally prepared for a nontechnical audience and is well-illustrated with photographs of arches and waterfalls around the margins of the map. It discusses and shows the location of natural features such as fossil and mineral deposits, springs, arches, waterfalls, demoiselles, and scenic overlooks, and cultural features such as historic trails, modern jeep trails, mines, and drill holes. The increased visitation in the Monument area makes this map more relevant today than it was when it was published 14 years ago. The map of landforms is also informative for visitors who are interested in the landscape, but who may not have geologic training.

Surficial Geologic Map

Two geologic maps were produced simultaneously with the environmental geology study of the Kaiparowits Plateau area. One emphasized bedrock geology and the other emphasized surficial geology, which allowed more total information to be conveyed without either map becoming excessively complex. Surficial deposits were not shown on the bedrock geologic map, even where the underlying bedrock was completely covered, and the position of contacts and bedrock units had to be inferred.

On the surficial geologic map, areas of bedrock were subdivided into eight categories according to lithologic and geomorphic characteristics rather than stratigraphic divisions, and unconsolidated deposits were subdivided into 42 categories based on differences in depositional process, lithologic composition, and age of deposition. Depositional process is important because it indicates dominant geomorphic processes that have affected various parts of the Monument in the past and that may pose hazards in the future. Lithologic composition affects the chemistry, texture, and erodability of soils formed on the deposits, and thus controls certain aspects of plant distribution and landscape stability. The ages of episodes of deposition provide clues about the probability

that hazardous processes will recur over a given span of time.

Age

Surficial deposits on the map are generally subdivided into three broad age ranges of Holocene (< 10 Ka), late Pleistocene (10 to 40 Ka), and middle Pleistocene to Pliocene (40 Ka to 5 Ma). In the absence of quantitative control (except for one ^{14}C date and one archeological date), the estimated ages were based primarily on geomorphic preservation and position. The lack of age control is a major weakness of the mapping and limits its usefulness for hazard analysis. More recent investigations have been able to refine the chronology of the younger deposits with more radiocarbon dates, and new techniques of cosmogenic dating offer promise in quantifying ages of the older deposits.

Lithologic Composition

Surficial deposits were subdivided according to the dominant lithology of the larger clasts. These were generalized into categories of sandstone, quartzite cobbles, limestone, volcanics, sand, and silt. Deposits containing quartzite cobbles from the Paleocene and Late Cretaceous Canaan Peak Formation, and those containing andesite and basalt boulders from the volcanics capping the Aquarius Plateau and Boulder Mountain, are unusually resistant to erosion and comprise most of the oldest and highest terraces.

Bedrock outcrop areas were generalized as volcanic rock, volcanic conglomerate, limestone, quartzite-cobble conglomerate, shaly rock, interbedded sandstone and shale, massive sandstone, and rock baked by burning coal.

Depositional Process

Deposits were subdivided on a genetic basis into alluvium, colluvium, eolium, residuum, and bedrock. Alluvial deposits include sediment in active stream channels, floodplains, alluvial fans, several generations of terraces, and thin veneers overlying pediments. Colluvial



depositional processes included hillside creep, rockfall, and several forms of landsliding. Wind action deposited eolian sand in the lowlands and silt at higher elevations. Residuum is the residue of weathering processes that accumulates where slopes are too gentle for removal by colluvial processes. Bedrock areas were mapped where erosional processes dominate and sediment does not accumulate, so that at least half the surface is free of even thin colluvium.

Landslides

The most spectacular geomorphic processes that have affected the area of the Monument are the giant landslides. Major flows occur where rocks from the Straight Cliffs Formation fall onto Tropic Shale along the Straight Cliffs, where tuffaceous sediment surrounding the Aquarius Plateau and Boulder Mountain flows out beneath the overlying volcanic rock, and where Wasatch (Claron) Limestone cliffs collapse around the Table Cliffs Plateau. Sediment from landslides and debris flows washed far beyond the slide toes to produce unusual geomorphic forms that contribute to unique scenic characteristics of the Monument. Along the southern Straight Cliffs, some of the most spectacular deposits of large sandstone blocks in shaly matrix form lobate ramps within reentrants in cliffs of Dakota Sandstone and the Morrison Formation below the bench of Tropic Shale. Debris washed from these ramps periodically buries minor channels and spreads widely across the bench of soft Entrada and Carmel Formation sediments at the foot of the Straight Cliffs, but becomes channelized into thick, narrow fills when it enters the deep, steep-sided canyons that start at the top of the Navajo Sandstone. The thick fills of coarse debris may be more resistant to erosion than the sandstone bedrock, but, in any case, commonly deflect the canyon streams from the axis of their bedrock canyons so that post-fill incision becomes superposed on bedrock spurs and parts of the canyon walls to produce incongruously narrow slit canyons that alternate with much wider canyon reaches. Excellent examples of the process are found along Coyote Gulch.

In the Boulder/Burr Trail area, similar processes occur, but there the debris includes very resistant large boulders of basalt and andesite that render debris deposits much more resistant to erosion than the sandstone bedrock. As a result, topographic inversion abounds, and all the highest ridges are former bedrock valley bottoms now armored by debris.

Recurrence of major landsliding events is inevitable and must be considered in locations of facilities and cautions to visitors who may not recognize the possibilities. The spectacular scale and obviousness of cause and effect offer opportunities for interpretation and increasing public awareness of natural processes. Rockfall is a more localized, but significant, hazard. Areas of extensive rockfall deposits are delineated on the surficial geologic map.

Streamflow and wind transport are also processes that have management implications. Areas of recent stream deposits are subject to hazards of flash flooding and bank erosion. Most areas of eolian (wind) deposits are partially stabilized by vegetation, but are sensitive to disturbances that can remobilize the sand and decrease biologic productivity.

Conclusion

Understanding surficial geology and geomorphic processes in the Grand Staircase-Escalante National Monument is important for the following reasons:

1. The geomorphic processes and the scenery they produce are a vital component of the natural ecosystem and are specifically mentioned in the Presidential proclamation as one of the reasons for establishment of the Monument.
2. The Monument is a major educational resource for teaching natural science. Lack of thick vegetation and the large scale of some of the natural geomorphic processes make them unusually obvious and easy to understand. The staff of the Monument has



a great responsibility to understand the science and interpret it for visiting students of all ages.

3. Some geomorphic processes constitute natural hazards that are not obvious to the general public. Administration of the Monument must include planning for such hazards and appropriate warnings for visitors.
4. The deposits and active processes form the basis for engineering geology analyses necessary for the location and design of any buildings, campgrounds, bridges, or roads within or near the Monument.
5. Construction in or near the Monument may require aggregate. Potential sources can be located from the map of surficial deposits.

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PALEONTOLOGY







Emerging Importance of the Grand Staircase-Escalante Region in Cretaceous Vertebrate Biostratigraphy, Western U.S.

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ABSTRACT

■ There has been a long tradition in North America of studying sequential vertebrate faunas. This kind of study, known as biostratigraphy, dates from the 1880's when paleontologists such as Edward Drinker Cope began to use terms for fossil vertebrate faunas that are still used today. In 1941, the vertebrate (or mammal) ages for the Cenozoic Era (last 65 million years) in North America were more formally defined by the Wood Committee. These have recently been redefined and brought up to date (Woodburne, 1987).

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The Wood Committee mentioned, but did not formally name, a pre-Cenozoic age that they called the Lancian, after faunas from the Upper Cretaceous Lance Formation in eastern Wyoming. The formal naming of the Lancian as well as other Late Cretaceous vertebrate ages did not occur until Russell (1964, 1975) named four Late Cretaceous ages—Aquilan, Judithian, Edmontonian, and Lancian (Figure 1). The youngest and best studied is the Late Cretaceous Lancian. Lancian faunas from Wyoming have been described by Clemens (1964, 1966, 1973) and Estes (1964), those from Alberta have been described by Lillegraven (1969), and those from Montana have been described by Archibald (1982) and Bryant (1989). The next older Edmontonian is the least well-known age, with sites in central Alberta and possibly northwestern Colorado. The Judithian mammal age is known by faunas from Montana (Sahni, 1972; Montellano, 1992), Alberta (Fox, various papers), and Wyoming (Lillegraven and McKenna, 1986). There are also faunas from northern New Mexico and Texas that may be referable to the Judithian or possibly the next younger Edmontonian mammal age. The Aquilan age is almost as poorly known as the Edmontonian, and at present is only reported from Alberta (e.g., Fox, 1971).

Until the 1980's, sites in Utah played essentially no role in our understanding of the biostratigraphy of Cretaceous vertebrates. This all changed with the discovery of Cretaceous vertebrate faunas from the Henry Mountains and the Kaiparowits Plateau, and more recently from the Paunsagunt and Markagunt Plateaus and the western flank of the San Rafael Swell. Most of these discoveries have been the work of Eaton and Cifelli and their colleagues (e.g., Cifelli, 1990; Cifelli and Eaton, 1987; Eaton, 1995). Of greatest concern for the Grand Staircase-Escalante National Monument are the fossil faunas discovered

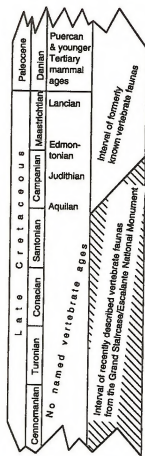


Figure 1. Late Cretaceous and early Tertiary mammal ages in North America, in reference to mammal faunas of the Grand Staircase-Escalante region.

in and around the Kaiparowits Plateau in the heart of the Monument. The vertebrate fossils that have been recovered from this region are important in their own right as they add new information on the evolutionary history of many vertebrate groups. These new faunas also provide very important new biogeographic and biochronologic extensions for the previously known Cretaceous faunas described above. Biogeographically, they fill a void between the sites to the north in Wyoming, Montana, and Canada, and to the south in New Mexico and Texas. Probably even more importantly, they provide a major time extension older than the Judithian described above—all the way back to near the beginning of the Late Cretaceous (Figure 1). Although publications have already appeared about the faunas from the Kaiparowits Plateau and the surrounding region, there is no doubt that much more information will emerge about these very important area.

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A Decision Model for Managing Paleontological Resources on Public Lands Using Spatial Data

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The BLM employs three staff paleontologists, each providing expertise to managers and field office staff in several western states. Because the BLM administers some 264 million acres, it is unreasonable to expect that three individuals can be responsive to every need relating to paleontological resources. Instead of working harder, the BLM is using technology in order to work smarter. The decision model described here allows BLM paleontologists, managers, and field

ABSTRACT

■ The Bureau of Land Management (BLM) manages access to paleontological resources for scientific, educational, and recreational purposes on some 264 million acres of public land, primarily in 11 western states. Technological tools are increasingly used to prioritize work and guide management decisions by predicting areas where impacts to significant fossils are likely to be the greatest.

In connection with its participation in the multiagency Northern Great Plains (NGP) Ecosystem Assessment Project, BLM Wyoming has been using geographic information systems (GIS) tools such as Arc/Info and ArcView to build spatial data layers that integrate data in a graphic format. Information in this format is more accessible and understandable than it would be in tabular or other formats. Because digital data layers such as geologic and land ownership maps already exist, our primary task for this project was to locate and compile the layers in compatible scales and formats, and to devise queries that would address our concerns about paleontological resources. A critical component was to develop paleontological sensitivity rankings and management recommendations for individual geologic units. A pilot project for Wyoming is now underway, and coverage of the western United States is anticipated by 2002.

Earlier projects (Foss and Sherman, 1997; Reynolds, 1997) focused on small areas and did not address paleontological sensitivity or management recommendations, elements that are unique to BLM's project. Fossil locality data can be added as an attribute layer for areas where this detail is available and needed, but it should be considered sensitive. Use of such decision models will enable managers to limit negative impacts to nonrenewable fossil resources and direct visitor attention to areas where recreational or interpretive activities are most appropriate.

office staffs to identify and focus attention on only those areas where paleontological resources require management.

Under the Federal Land Policy and Management Act (FLPMA) of 1976, the BLM



is required to manage the public lands for multiple uses. That means that public lands are managed so that a variety of uses may be considered appropriate for any given area. Thus fossil collecting often occurs in areas that are also managed for oil and gas production, wildlife habitat, wilderness values, and pipeline rights-of-way. The BLM allows fossil collecting for scientific, educational, and recreational uses; vertebrates may be collected only under a permit and remain in the public trust, while common invertebrates and plants are available for collection by school groups and hobbyists. Petrified wood may be collected for personal use and for sale if a permit is obtained.

Using Geographic Information Systems (GIS)

Land managers need to know where fossils occur on the lands they manage, what kinds of fossils are present, what uses are appropriate, and what impacts and opportunities to expect. Though simple sensitivity maps have been developed to provide this information, producing them by hand is difficult and time-consuming, and their use is limited. Making changes is also time-consuming. Our project uses GIS tools such as Arc/Info and ArcView to acquire and manipulate large amounts of data in a graphic format much more quickly and accurately than would ever be possible without such techniques. GIS can be used to display spatial data in the form of maps. Data layers or themes such as topography, roads, streams, and geology can be overlaid and displayed for visual inspection. Fossil locality information can be graphically displayed so that sites can be cataloged and monitored (Foss and Sherman, 1997; Reynolds, 1997). However, as Foss and Sherman suggest (1997) the technology is capable of far more. Fiorillo et al. (1997) refer to a developing model for use in units of the National Park Service that will be similar in approach to this model.

A decision model for paleontological resources requires a number of data layers, including

geology, topography or digital elevation models (DEM's), transportation (roads, railroads, pipelines), place names, land status (private, state, public, and other Federal), soils, and vegetation. The data layers used in this project were located and acquired by staff at BLM's National Applied Resource Sciences Center (NARSC) in Denver, CO, and then put into compatible formats and scales. To test the model, fossil locality data for the Bridger Basin in southwest Wyoming was obtained from the University of Colorado Museum, which has collected vertebrate fossils under a BLM permit for many years and maintains an accurate and extensive locality database. We chose to develop a pilot project in the Bridger Basin because the Bridger Formation (middle Eocene, about 50 million years old) yields scientifically significant fossils in an area where they are readily accessible, but where some human activities may cause negative impacts if not regulated. Although the pilot area is small, it is clear that the decision model will be useful and valid at many scales over large areas.

Another feature of GIS is the ability to integrate many kinds of graphic data, from photographs to videos to stratigraphic sections that are linked to specific map locations. We included examples of these in our project to suggest their utility.

Building the Model

Our decision model was built by querying the data layers to isolate and quantify areas where management of paleontological resources is necessary, as opposed to areas where no action is required. First, we evaluated each geological formation using a method developed by Cathleen May for the USDA Forest Service. The method involves searching on-line databases of geological literature using specific search strings to locate publications on fossils. Each formation is assigned a ranking from Class 1 (least sensitive) to Class 5 (most sensitive) in the Fossil Yield Potential Classification (FYPC). The FYPC also includes a range of management options or recommendations for



each class, giving land managers, for the first time, concrete guidelines aimed at making the best possible use of fossils on the public lands.

Using the resulting geologic map with sensitivity rankings, we then superimposed other data layers in order to identify additional factors that increase an area's likelihood of yielding fossils. For the Bridger Formation, we displayed fossil locality data only to test the validity of our hypothesis.

Results

The decision model we built accurately delimits areas where fossils of various kinds are known to occur and where management should be applied. One of the most striking results from the model was the close correlation of exposed rock or badlands with public land boundaries. Because steep, barren lands were not suitable for homesteading, they often remained in Federal ownership and are now administered by the BLM; these exposures are the places where fossils are most often found. The BLM thus administers millions of acres of land that are far more likely to produce fossils than forage or food crops.

In the Bridger Formation (Class 5 or highly sensitive), vertebrate fossils occur primarily on: 1) areas of bare ground or thin soils with 2) thin vegetation such as sagebrush or prairie grass, and frequently, on 3) steep, highly eroded slopes. By selecting these polygons in ArcView and superimposing a land status layer that further identifies only those areas administered by the BLM, we were able to reduce the area where management of fossils was potentially necessary by about 50 percent in the project area. ArcView calculated the number of acres, and could also calculate the number of miles of road which might need to be patrolled, or the number of acres within a 1-mile distance of roads, for example.

Further Options

Potential uses of this decision model have yet to be explored. We expect to use it, for example, to identify areas for recreational collecting of fossil invertebrates. An ideal area for recreational collecting would have easy access, relatively gentle slopes, and no safety hazards or conflicts with other resource uses on public lands where certain Mesozoic marine units crop out. The model will also be used to locate interpretive sites, and to focus research activities where more needs to be known about paleontological resources.

It would be possible to acquire the necessary data layers, query them, and produce results for all the western states on various scales. However, it is more reasonable instead to distribute a CD version of the project summary, including specific instructions for creating a similar tool for local areas where need and interest are particularly high. Training in the use of the application and the resulting product will be offered to field offices and other interested users.

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Paleontologic Inventory of Marine and Brackish-Water Late Cretaceous Rocks in the Grand Staircase-Escalante National Monument, Utah

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ABSTRACT

■ An inventory of marine and brackish-water invertebrate fossils from Late Cretaceous rocks has been compiled for the newly designated Grand Staircase-Escalante National Monument based on U.S. Geological Survey collections obtained during the past three decades. The inventory contains identifications and descriptions of invertebrate fossils from more than 100 localities, and supporting detailed stratigraphic and lithologic information for several measured sections from the upper part of the Dakota Formation, Tropic Shale, and Straight Cliffs Formation, which include rocks of late Cenomanian through early Campanian age. Some of the identified fauna were not previously reported from southwest Utah.

For many fossil localities, the inventory provides data on the presence of ammonites and bivalves, which are used to correlate marine Cretaceous rocks in southwest Utah with equivalent rocks in other regions. The inventory also contains: 1) information on the geologic age, lithologic characteristics, and depositional environments of rock units; 2) a map of the Monument illustrating fossil localities; and 3) a stratigraphic chart showing correlations with equivalent rocks at the international Cenomanian-Turonian boundary reference section near Pueblo, Colorado, based on ammonites and bivalves.

Correlation of marine Cretaceous rocks in the Grand Staircase-Escalante National Monument with the Cenomanian-Turonian boundary reference section is a sample research application for the inventory. The oldest marine shale of the Tropic transgression occurs in the early late Cenomanian *Metoicoceras mosbyense* biozone of the Dakota Formation in the western part of the Monument at Cottonwood Wash. Marine sandstone in the Straight Cliffs Formation represents the fluvial regressive phase of the Tropic and contains biozones ranging from late middle Turonian to early Campanian. At Pueblo, the oldest marine fauna above the Dakota is in the Graneros Shale in the early middle Cenomanian *Conlinoceras tarrantense* biozone, whereas the late middle Turonian *Prionocyclus hyatti* biozone occurs in the middle part of the Carlile Shale.



Other applications for the inventory include studies of the energy, mineral, and environmental resources of the Monument. Information gathered from the inventory has been directly incorporated into education outreach activities in the surrounding school districts in the form of lectures, field trips, and teacher training programs. Graduate school theses and other academic research projects are also currently underway. The inventory is available through the Bryce Canyon Natural History Association, Bryce Canyon National Park.



Cretaceous Vertebrates of the Grand Staircase-Escalante National Monument

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Significant collection of vertebrates within the Cretaceous section of the Grand Staircase-Escalante National Monument was initiated by Eaton (then at the University of Colorado, Boulder) and Cifelli (then at the Museum of Northern Arizona) in 1983. This led to a cooperative research project. Since that time, research has continued for 15 years and other workers (see references) have participated both in field research and publishing information on the recovered fossils.

Eaton and Cifelli's initial research was directed primarily at large gaps in the record of mammalian evolution during the middle Cretaceous that had been documented in Lillegraven et al., 1979. These gaps also existed for other vertebrate groups.

ABSTRACT

■ Over the past 15 years, intensive sampling of vertebrates have been undertaken by workers at several institutions within the Cretaceous rocks of the Grand Staircase-Escalante National Monument. Although surface collection has contributed to our understanding of the Cretaceous vertebrate fauna, time- and labor-intensive methods employing screen-washing techniques have been responsible for the vast majority of the taxa reported from the area.

The research was undertaken with specific questions in mind, not to simply collect objects for their own sake. Recovered vertebrate faunas have provided many new records of vertebrates and answered questions about evolutionary relationships and extinction events, and have also raised new questions. The collections represent the most continuous record of vertebrate evolution spanning the early Late Cretaceous in the world.

Land managers should develop policies that do everything possible to preserve documented localities and prevent unpermitted collection within the Monument. Land managers can also act as facilitators for researchers and to help link research within the Monument to education of the public. However, the process and direction of research should be determined by scientists distinct from the process of land management.

Mammals during the Mesozoic were very small, similar to the size of rodents today. The parts of these ancient mammals most likely to be preserved are their durable, but tiny (a few mm), enameled teeth. To recover these microfossils, techniques were employed to collect matrix from localities where small bones had been observed. This matrix was then processed by a method referred to as "wet-screening." The matrix was dried and then poured into nested screens, one with a standard-size window screen and another with a much finer screen. This material was then sifted in water to remove clays, silts, and small sand-sized particles. The remaining concentrate was then



dried and picked under a microscope to recover fossils. Mammals are relatively rare in middle Cretaceous rocks and often many tons of matrix were processed from a single locality. During a single field season, often only a few localities would be thoroughly sampled, and then it would take months or years to pick the resultant concentrates.

This labor-intensive method has produced thousands of vertebrate and invertebrate specimens representing the isolated remains of lizards, frogs, crocodylians, dinosaurs, fish, birds, and mammals. The diversity of vertebrates reported in Eaton, Cifelli et al. (in press), and reproduced in Gillette and Hayden (1997) is largely the result of screen-washing, although the surface collection work of J. Howard Hutchison (University of California, Berkeley) and others has done much to augment our knowledge of dinosaurs, crocodylians, and turtles.

Geologic Setting

The Kaiparowits Plateau (Figure 1) contains a thick (2-km) sequence of Upper Cretaceous, largely non-marine rocks spanning the Cenomanian through Campanian stages (Figure 2) (Gregory and Moore, 1931; Peterson, 1969a, b; Eaton, 1991). The sequence formed in the foreland basin of the Sevier orogenic belt with detritus shed principally from the west and southwest (Eaton and Nations, 1991). The Cretaceous Western Interior Seaway advanced into the area from the east during the late Cenomanian. Although deeper waters withdrew from the area in the Middle Turonian, there was strong marine influence on depositional sequences along the eastern margin of the Plateau through the Santonian. By the Campanian, the sea had withdrawn to a position well east of the Henry Mountains,

and there are no brackish water or marine environments recorded in the Campanian rocks of the Plateau (Eaton, 1991).

The stratigraphic sequence (Figure 2) on the east side of the Plateau is only interrupted by marine deposits during the late Cenomanian to middle Turonian. The rest of the sequence is nonmarine and represents one of the thicker nonmarine Cenomanian-Campanian sequences in the world.

Comments on the Vertebrate Faunas

Initial faunal lists for the Cretaceous Kaiparowits sequence were published by

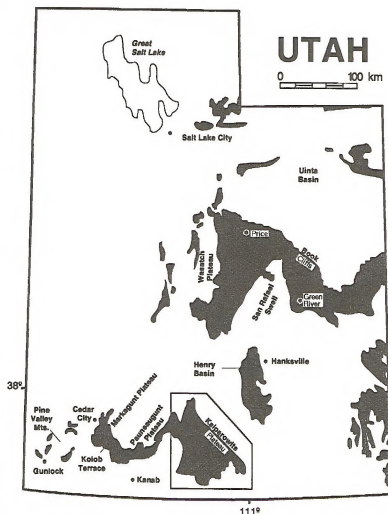


Figure 1. Cretaceous outcrop map of Utah (based on Hintze, 1974) showing the geographic location of the Kaiparowits Plateau.



STAGE	FORMATION	MEMBER	THICKNESS m
Campanian	Kaiparowits		885
	Wahweap	capping ss	357-458
		upper	
middle			
lower			
?			
Santonian	Straight Cliffs	Drip Tank	295-493
John Henry			
Coniacian			
Turonian		Smoky Hollow	
		Tibbet Canyon	
	Tropic Shale		186-215
Cenomanian	Dakota	upper	4-51
		middle	
		lower	

Figure 2. Generalized stratigraphy and ages of Cretaceous units of the Kaiparowits Plateau (modified from Eaton, 1991).

Eaton and Cifelli (1988); an updated faunal list should be published in the near future (Eaton, Cifelli et al., in press). Our data formed the basis for the faunal list that was reproduced in Gillette and Hayden (1997). As these faunal lists are already available, they will not be reproduced here, and only a few key results of the research will be discussed below.

Dakota Formation

The basal unit of the Cretaceous sequence rests on an unconformity of significant duration,

cut into the middle Jurassic Entrada Formation on the western side of the Plateau and into the Upper Jurassic Morrison Formation on the eastern side. All existing evidence suggests that the entire Dakota Formation is of late Cenomanian age (Eaton, 1991, 1995).

The Dakota Formation contains fluvial, paludal, lacustrine, brackish water, and marine environments. Most of the material described here was recovered from floodplain deposits, and although localities have been found in other paleoenvironments, particularly lacustrine, little work has been done on those faunas.

The fauna of the Dakota Formation marks a transition between older faunas and those characteristic of the Late Cretaceous. Certain archaic relics of the Jurassic, such as the turtle *Glyptops* sp. and the fishes *Lepidotes* sp. and *Ceratodus* sp., are present in the fauna, along with the first relatively diverse assemblage of metatherian mammals (Cifelli and Eaton, 1987; Eaton, 1993). The dinosaurs are of relatively low diversity and dinosaur remains (even teeth recovered by screen-washing) are relatively rare in sampled localities (Parrish and Eaton, 1991).

Straight Cliffs Formation

The Straight Cliffs Formation spans the middle Turonian through the Santonian and is divided into four distinct members (Peterson, 1969a). The stratigraphy is summarized in Eaton (1991).

Tibbet Canyon Member

The Straight Cliffs Formation records the Greenhorn regression in the middle Turonian Tibbet Canyon Member. The member is dominated by sandstones that represent lower



shore face overlain by upper shore face deposits. The most common vertebrates recovered from this unit are sharks, but screening of two deltaic localities in the upper part of the member resulted in the recovery of other vertebrates, including mammals.

There has been little study of the specimens recovered from this member, which includes sharks, rays, lepisosteid fishes, crocodiles, and fragmentary teeth of marsupials. Identified chondrichthians include *Chiloscyllium greeni*, *Squalicorax falcatus*, *Scapanorhynchus raphiodon*, and *Cretodus semiplicatus*.

Smoky Hollow Member

The seaway temporarily withdrew to somewhere east of the Kaiparowits Plateau during deposition of the overlying Smoky Hollow Member. This member contains coal and some brackish paludal deposits in its basal part following the retreating shoreline eastward. The lower brackish parts have only been sampled for vertebrates in the Markagunt Plateau region (see Eaton, Diem et al., in press), but would undoubtedly produce brackish water fish faunas in the Kaiparowits region. The upper part of the member contains both lacustrine and floodplain paleoenvironments and has produced abundant microvertebrates (Cifelli, 1990c; Cifelli and Madsen, 1986; Eaton, 1995).

The fauna of the Smoky Hollow Member does not contain any of the archaic elements present in the Dakota fauna (e.g., *Lepidotes* sp., *Ceratodus* sp., *Glyptops* sp.) and is completely Late Cretaceous in composition. The comparison of the fauna recovered from the Smoky Hollow Member and the Dakota Formation has made it possible to document how terrestrial faunas in southwestern Utah responded to a global extinction event at the Cenomanian-Turonian boundary (Eaton et al., 1997).

John Henry Member

There was a significant transgression of the seaway that began in the mid-Coniacian; by the Santonian, the strand line was established in the middle of the Kaiparowits Plateau

(Eaton, 1991). Minor fluctuations in relative sea-level occur throughout John Henry deposition, but in general, the John Henry Member is primarily marine along the eastern margin of the Plateau and brackish water to nonmarine along the western margin. Because of our interest in mammals, most of the localities that have been worked are from the west side of the Plateau (except for some of the sharks that were collected by Hutchison from the eastern part of the plateau). There is a large brackish component to the fauna due to the nearby influences of the seaway, and mammals and other fully terrestrial components of the fauna are relatively rare in this member.

Drip Tank Member

The uppermost member of the Straight Cliffs Formation is the Drip Tank Member. It is composed predominantly of sandstones deposited by braided and meandering streams (Eaton, 1991). Rare thin layers of mudstones are also present. Only water-worn fragments of turtle and crocodile have been recovered from this member. There is no basis for dating this member other than stratigraphic position.

Wahweap Formation

The sediments of the Wahweap Formation were deposited predominantly by meandering streams during the early part of the Campanian. The formation is overall not very fossiliferous, with the most productive known horizons occurring in basal lag deposits of streams. There is no evidence of either brackish water or marine deposits in the formation, as the seaway had retreated well to the east by the Campanian (Eaton, 1987, 1991). The early Campanian age is based in part on the similarity of the fauna to that reported by Fox (1971) from the Milk River Formation of Canada. The Wahweap is also correlative to the Masuk Formation to the east (Peterson and Kirk, 1977) from which palynomorphs indicate a post-Santonian age, and mollusks in the underlying Blue Gate Member of the Mancos Shale indicate an age for the upper part of the member close the Santonian-Campanian boundary (Eaton, 1990).



We are following the standard application of ammonite-based zonal terminology developed by Cobban (e.g., 1993); however, a recent challenge to the orthodox correlation of North American ammonites to European stages was presented by Leahy and Lerbekmo (1995). If their evaluation is correct, then both the Milk River and Wahweap faunas may be late Santonian in age or span the Santonian-Campanian boundary.

The Wahweap fauna is notable for its abundant marsupials (Cifelli, 1990b) and the first definite occurrence of eutherian (placental) mammals in the region (Cifelli, 1990d). Assuming contemporaneity with the upper Milk River Formation of Alberta, this occurrence represents the oldest unambiguous record of eutherians from North America, although specimens in the Smoky Hollow Member of the Straight Cliffs Formation hint at a much earlier occurrence.

Kaiparowits Formation

This formation represents more than 800 m of Campanian strata deposited by large rivers with broad alluvial floodplains (Eaton, 1991). Localities occur in the sandstones associated with rivers and in the mudstones associated with floodplain and lacustrine environments. The Kaiparowits Formation is the most fossiliferous of Cretaceous units on the Plateau.

Fossils are most common in the lower half of the formation. Eaton and Cifelli (1988) suggested that this might be an artifact of extensive badlands being well-developed in the lower part of the formation, while the upper part has limited access due to steep topography controlled by the overlying Canaan Peak and Claron formations. Although this may in part be true, work in subsequent years suggests the upper part is actually not as fossiliferous as the lower.

When the preliminary report was published, there was an attempt made to separate the fauna of this thick formation into lower and upper faunas, but it is evident from Eaton and Cifelli (1988) that there is no significant

faunal distinction; however, there is some indication of up section change in the fauna, including the first occurrences of *Paranyctoides* sp., *Gypsonictops* spp., and some marsupials such as *Alphadon attaragos* in the upper part of the section (Cifelli, 1990a, d). Nonetheless, it appears this thick formation was deposited relatively quickly in a rapidly subsiding basin (Eaton, 1991).

The age of the fauna is determined mostly by palynomorphs (Eaton, 1991; Nichols, 1997) and the lack of diagnostic Maastrichtian mammals. The stratigraphically highest locality from which significant amounts of matrix have been processed is about 200 m below the top of the formation. Therefore, it is unknown if the Kaiparowits Formation could cross the Campanian-Maastrichtian boundary, but palynomorph samples (Eaton, 1991) appear to be Campanian in age and lack diagnostic Maastrichtian taxa (Farabee, 1991).

Perhaps most distinctive of the Kaiparowits fauna is the first appearance of the insectivore *Gypsonictops* sp. (Cifelli, 1990d), which may be a good index fossil for the beginning of the Judithian North American Land-Mammal "Age" (Cifelli, 1994). Among the turtles, kinosternoids and the baenid *Boremys* sp. first appear, and the pleurosternid *Compsemys* is common. Sharks become much rarer, with *Ischyrrhiza* sp. and *Hybodus* sp. known only from a single locality near the base of the formation (locality FB1, Figure 3 in Eaton and Cifelli, 1988). The multituberculate mammals were identified in Eaton (1987). Multituberculates from the Wahweap compare closely to forms described from the Milk River Formation, but the Kaiparowits taxa do not compare well to any fauna and include many new forms.

Conclusions

The Kaiparowits Plateau contains a remarkable record, currently the best in the world, of vertebrate evolution from the late Cenomanian through the Campanian. The enormous



number of specimens recovered from the Plateau include many new taxa and new temporal and geographic occurrences. Mammals have been the most studied of the classes and an enormous amount of work remains to be done on the lower vertebrates. Recently discovered localities that appear to be very productive suggest that the collections reported herein mark only the beginning, and that decades, if not centuries, of research remain to be accomplished.

This record of Cretaceous vertebrates is significant globally and land management policies should serve to protect this remarkable resource. As new questions are asked and new methodologies developed, researchers will return to the monument to undertake research for generations to come. Land managers can act to facilitate this research and encourage public education, but should not try to direct the nature of scientific inquiry.

Acknowledgments

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Paleobotany in the Grand Staircase-Escalante National Monument and Adjacent Areas in Southern Utah

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To date, there have been few published paleobotanical studies on plant fossils collected from within the boundaries of the Grand Staircase-Escalante National Monument (GSENM). However, ongoing work primarily by vertebrate and invertebrate paleontologists shows that the Monument is virtually an untapped paleontological resource for all fields of paleontology. Intensive field work and research on marine and nonmarine Cretaceous vertebrates of the Kaiparowits Plateau region within the last 15 years by Jeffrey Eaton (Weber State University, Ogden, UT), Richard Cifelli (Oklahoma Museum of Natural History, OK), and their colleagues has been instrumental in elucidating the research potential of the Monument. In addition to vertebrate fossils, these investigators have collected and noted the occurrences of plant and invertebrate fossils throughout the GSENM, as well as provided palynologists with rock samples yielding abundant pollen

ABSTRACT

■ Little has been published on paleobotanical collections from the Grand Staircase-Escalante National Monument. However, field work by vertebrate paleontologists in the Cretaceous Kaiparowits Plateau region has expanded not only our knowledge of the ancient faunas that once inhabited southern Utah, but also has brought to light the potential for paleobotanical investigations. In addition to fossil wood occurrences, numerous sites yielding compression floras are now known from the Kaiparowits region. Preliminary study of a University of California Museum of Paleontology (UCMP) collection from the Campanian Kaiparowits Formation has revealed material similar to *Hydropteris pinnata* Rothwell et Stockey, an extinct water fern described from the Maastrichtian of southern Alberta, Canada. *Hydropteris* combines features of three orders: the Marsileales, Salviniaceae, and Filicales. Similar leaves also occur in the Maastrichtian of Wyoming. The Utah material now represents the earliest record and southernmost occurrence of this fern. Plant fossils provide not only important paleofloristic information, but also data for reconstructing paleoclimates. Management of the GSENM's paleobotanical resources should include scientific evaluation of all types of plant fossils.

and spores. Their work has brought this area to the attention of many paleontologists and demonstrates the importance of developing a sound management plan to conserve these resources not only for future generations of paleontologists, but for everyone.

Paleobotany and Its Importance

Although paleobotany often takes a back seat to vertebrate and invertebrate paleontology, these organisms (especially those living in the



terrestrial realm) owe their existence to plants. There would be no dinosaurs, mammals (including humans), marsupials, birds, reptiles, insects, or fishes. The Earth's vegetation right up to the present has shaped and supported all other forms of life, including our own, by providing breathable air, habitats, food, and fuel.

Paleobotany is the study of fossil plants. Although not plants, fossil fungi are typically studied by paleobotanists as well since these organisms often get preserved along with their plant hosts. In general, plant fossils fall into two categories. Those that are visible to the naked eye, such as leaves, stems, roots, and reproductive structures, are referred to as megafossils, whereas plant microfossils include primarily pollen and spores (palynomorphs). As with vertebrate fossils, plants are rarely found fully articulated or preserved with all their parts in organic connection, but more commonly as assemblages of isolated organs. One of the principle goals of paleobotanists, among many, is to reconstruct whole plants whenever possible. Having the entire organism allows one to recognize the range of morphological variation in plant organs (especially leaves) exhibited by an individual species. Knowing the range of variation within a fossil species enables paleobotanists to better estimate the actual taxonomic diversity that was present in the past, and to better understand the evolutionary history, systematic relationships, paleobiogeography, and paleoecology of plants through time.

Because plants are sensitive to climate and climatic change, fossil plants continue to be instrumental in reconstructing terrestrial paleoclimates (Wolfe, 1995; Wilf, 1997) and providing important tests for paleoclimates derived from computer-generated global circulation models (GCM) (Sloan and Barron, 1990, 1992; Wing, 1991; Wing et al., 1991; Wing and Greenwood, 1993). Adaptations of plants to climate are reflected not only in leaf size, shape, thickness, cuticle anatomy, morphology of leaf margins, apices, and bases, but also in wood structure (e.g., Upchurch and

Wolfe, 1987; Wolfe and Upchurch, 1987a). Over 80 years ago, Bailey and Sinnott (1915) and Bailey (1916) noted in modern forests a strong correlation between climatic warmth and the percentage of dicot species with toothed vs. smooth-margined (entire) leaves. They found that in mesic, tropical forests, a high percentage of dicot species had smooth-margined leaves, whereas in mesic, temperate forests, the highest percentage of dicot species bore nonentire leaves. Wolfe and others have expanded on these earlier studies by using modern analytical methods of quantifying and correlating the physical characteristics of dicot leaves with such climatic parameters as mean annual temperature (MAT), mean annual range of temperature, and those characteristics related to water availability, then applying these relationships to fossil leaf assemblages for inferring paleoclimatic conditions (e.g., Wolfe, 1971, 1979, 1993, 1995; Wilf, 1997). In general, floras with a high percentage of species that have large, smooth-margined leaves with elongated tips are indicative of warmer and wetter climates, whereas a high percentage of smaller, or serrate-margined leaves indicates cooler or drier, more temperate conditions. Today for example, in areas with MAT of 20 °C smooth-margined species may comprise 60-70 percent of the flora. The use of leaf physiognomic methods on fossil compression floras is now one of the most reliable for estimating past terrestrial climates. In addition to leaves, fossil woods (including palm wood) can also provide information about past climate. Woody dicotyledonous plants growing in tropical areas, for example, typically lack well-developed growth rings. Generally, the presence of growth rings is characteristic of plants growing in a seasonal climate marked by distinct wet and drier periods throughout the year. As such, growth ring thickness in many cases is correlated with the relative amount of precipitation in a given year. Likewise, the presence of fossil palm wood indicates warm, subtropical to tropical conditions with frost occurring rarely or not at all.



Paleobotany in Utah

Paleobotanical work in Utah has been done largely outside the boundaries of the GSENM. The majority of these scientific investigations for more than the past 30 years were carried out by Dr. Sidney Ash (Weber State University, Ogden, UT) and Dr. William D. Tidwell (Brigham Young University, Provo, UT) in conjunction with their students and colleagues at other institutions. These workers have been the key contributors to our understanding of the composition and history of Utah's ancient plant communities, their relationship to other paleofloras of similar age, and the paleoenvironments and climatic conditions in which these floras lived and ultimately died (e.g., Tidwell, 1967, 1975, 1986, 1988, 1990; Tidwell and Rushforth, 1970; Scott et al., 1972; Tidwell et al., 1974, 1976; Furniss, 1975; Medlyn and Tidwell, 1975; Ash, 1976, 1982, 1987; Parker, 1976; Thayne et al., 1983, 1985; Thayne and Tidwell, 1984; Tidwell and Thayne, 1985; Tidwell and Jennings, 1986; Tidwell and Ash, 1990; Tidwell and Medlyn, 1992; Ash and Litwin, 1996). This work, and especially studies carried out at localities adjacent to the Monument, is important since the same or correlative formations within the Monument may yield additional fossil assemblages that are similar to or different from those already known.

Paleobotanical Studies in the GSENM

Within the Monument, strata range in age from the Permian to the Quaternary and all contain some form of plant fossils (Gillette and Hayden, 1997). Exceptions are the Permian Toroweap-White Rim Formations, the Jurassic Navajo Sandstone, Temple Cap Sandstone, Entrada Sandstone, and the Summerville, Henrieville, and Romana Formations (Gillette and Hayden, 1997). However, additional reconnaissance of these units by paleobotanists may reveal they also contain plant fossils. Despite the number of plant megafossil occurrences listed by Gillette and Hayden (1997), review of the literature

shows little has been published on this material. Rather, the majority of GSENM paleobotanical studies have been done by palynologists working on the pollen and spores from the Kaiparowits Plateau region largely for the purpose of dating and correlating the Cretaceous rock units in this area (Lohrengel, 1969; Orlansky, 1971; Bowers, 1972; May and Traverse, 1973; Nichols and Sweet, 1993; Bob Cushman, personal communication 1997).

UCMP Collections from the GSENM

Fossil plant collections from within the Monument, currently housed at UCMP, were made only over the last few years by J. Howard Hutchison (UCMP). These collections are from five localities. All localities are in Cretaceous formations with three of the sites yielding leaf compressions/impressions, while the other two are lignitic horizons. In addition to preserving megafossils, lignites often contain abundant pollen and spores, fruits and seeds, and dispersed plant cuticles.

The three UCMP compression/impression sites include the Alvey Wash plant locality (PA753), Johns Valley Borrow Pit NW (Pb97022), and the *Avisaurus* locality (PA674=V93097) (Figure 1). No attempt is made here to assign names to the Alvey Wash or Johns Valley material, but rather to report their occurrence in the Monument. As pointed out by a number of workers, the taxonomy

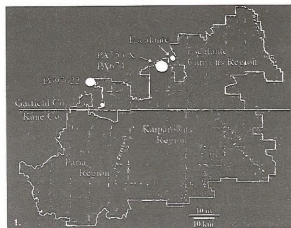


Figure 1. UCMP plant fossil localities in the Grand Staircase-Escalante National Monument.



and nomenclature of Cretaceous and Tertiary leaves are in a confused state (Dilcher, 1974; Hickey, 1973; Crabtree, 1987; Upchurch and Dilcher, 1990), making reliable identifications difficult. The problem of accurate identification is further compounded when material is fragmentary. In large part this confusion is the result of earlier workers assigning fossil leaves to modern genera based on their superficial resemblance to extant taxa. It is only within the last 25 years that paleobotanists have made a concerted effort to identify and classify leaf fossils using systems based on diagnostic leaf architectural characters (e.g., venation patterns, tip, base, and margin morphology) and cuticular anatomy (Dilcher, 1974; Hickey and Wolfe, 1975; Hickey, 1973, 1979; Upchurch and Dilcher, 1990; Johnson, 1996).

The Avisaurus Locality

Among the three GSENM plant localities, the *Avisaurus* locality is currently being studied by several UCMP researchers. The site is in Garfield County, T. 36 S., R. 1 W. At this site, compressed leaves and reproductive structures of an aquatic fern and carbonized wood were found co-occurring with freshwater pelecypods, gastropods, and a disarticulated *Avisaurus* skeleton within a gray mudstone unit. This unit is part of the Kaiparowits Formation. Age of the Kaiparowits has been considered either late Campanian or Maastrichtian based on palynomorphs (Eaton, 1991). However, reevaluation of the palynomorph record and additional evidence from mammalian faunas strongly support the Campanian age (Eaton, 1991; Nichols and Sweet, 1993).

Preliminary results show the Utah plant may be conspecific with *Hydropteris pinnata*, a new genus and species of extinct heterosporous leptosporangiate fern recently described from a thin, light gray siltstone horizon in the St. Mary River Formation of southern Alberta, Canada (Rothwell and Stockey, 1994). Frond, pinnae, and rhizome morphology of the Utah fern closely resemble those of *H. pinnata*. Moreover, remnants of the Utah sporocarps show lateral walls with indentations similar to those present in the Alberta fern. *Hydropteris*

pinnata combines the morphological features of three orders of modern ferns: the Marsileales, Salviniaceae, and Filicales. Habit and production of sporangia in sporocarps of *Hydropteris pinnata* resemble the Marsileales, the sporangial contents are similar to the Salviniaceae, while the pinnate leaves are typical of Filicales. As shown by Rothwell and Stockey (1994), this transitional fossil form has provided unique, new data for better understanding and further resolution of the phylogenetic relationships amongst heterosporous ferns.

Although not discussed by Rothwell and Stockey (1994), Dorf (1942) described similar fern leaf compressions as *Filicites knowltonii* Dorf from two localities (UCMP P3856=USGS 1462 and P3858) in the Lance Formation of eastern Wyoming. It is interesting to note that at the time, Dorf (1942) assigned the material to the form genus *Filicites* Brongniart and went on to state that the material was not comparable to any living or fossil ferns. Dorf's leaves from P3856 were recovered from a massive, buff to light gray claystone and found in association with other hygrophilous taxa such as *Equisetum*, *Trapa*, and *Typha*. At P3858, *F. knowltonii* was found in large dull gray siltstone concretions embedded in layers of lighter gray, sandy shales and not only in association with *Equisetum*, *Typha*, and *Trapa*, but also *Woodwardia* and *Pistia*. The age of both the St. Mary River Formation and the Lance is considered Maastrichtian. Therefore, if the age of the Kaiparowits is Campanian, then the *Hydropteris*-like plants in Utah represent the earliest and most southern record of this fern in North America, which raises interesting questions regarding its pattern of distribution. It also suggests that perhaps additional skeletal material of *Avisaurus* may turn up at the Alberta and Wyoming sites. Discovery of skull remains in particular would be especially important since much of what is known about this ancient bird is based on foot bones. Continued work involving the collection of additional fern specimens and processing of matrix for sporangial contents will help determine whether or not the Utah plant is conspecific with the Alberta and Wyoming material.



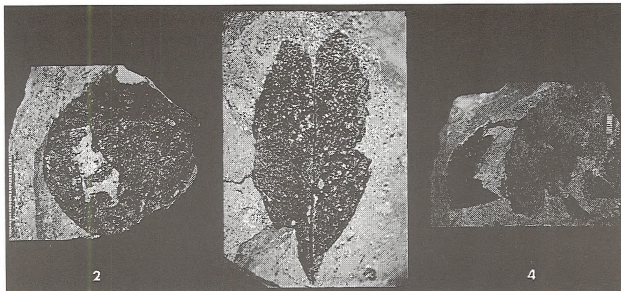
Alvey Wash Plant Bed

The Alvey Wash site is in the lower part of the Straight Cliffs Formation, possibly the Smoky Hollow member (needs to be field-checked). It is located near the town of Escalante, Garfield County, T. 35 S., R. 2 E. Age of the Straight Cliffs Formation extends from middle Turonian into the early Campanian based on marine mollusks (Eaton, 1991). The plant-bearing horizon lies just below a massive cross-bedded marine sandstone containing oysters and other invertebrate remains. The plant fossils consist of well-preserved dicot leaf compressions within a grayish tan mudstone (Figures 2-4), and so far, no ferns, cycadophytes, or conifers have been found at Alvey Wash. The Alvey Wash specimens show not only critical diagnostic characters for identification, such as overall leaf shape and fine venation patterns, but also may have cuticle preserved. Cuticle is the waxy outer covering found on leaves and all aboveground plant parts that are green and photosynthetic. Leaf cuticles are filmlike structures, highly resistant to diagenetic alteration, that preserve detailed features of the leaf surface, such as the outlines of epidermal cells, the stomatal apparatus, hairs, and glands. Cuticle may be preserved not only on the surfaces of whole leaf compressions (e.g., Upchurch and Dilcher, 1990), but also as macerates in rocks that otherwise appear to be devoid of plant fossils. In rocks where leaf

compressions might be lacking, leaf cuticle assemblages may be recovered that can provide important information regarding not only identity of the plants that were growing in the area, but also physiognomic characters useful in paleoclimate reconstructions (Wolfe and Upchurch, 1987b; Wolfe, 1993). The importance of leaf cuticles and pollen data was shown, for example, by Wolfe and Upchurch (1987b) in their analysis of dispersed leaf cuticles collected from 15 sections across the K-T boundary in the Raton Basin of Colorado and New Mexico. The cuticle data, in combination with data from leaf and pollen assemblages, showed that late Cretaceous vegetation in the Raton Basin underwent major ecologic disturbance due to an abrupt climate change coincident with or caused by a late Cretaceous bolide impact. The leaf and cuticle assemblages in particular suggested plant communities at the K-T boundary experienced a high rate of floral extinction followed by a slow recovery period.

Johns Valley Borrow Pit NW

The Johns Valley site is in the lower part of the Wahweap Formation. The site is located near Bryce Canyon, Garfield County, T. 36 S., R. 3 W. A preliminary analysis of the Wahweap mammals shows possible correlation with the early Campanian Milk River fauna of Canada (Eaton, 1991). Fossil leaves recovered



Figures 2-4. Dicotyledonous leaf compressions from the UCMF's Alvey Wash locality.



from the Johns Valley locality occur as impressions in a tan orange massive indurated sandstone. This assemblage appears to be more taxonomically diverse than Alvey Wash, consisting of several types of dicot leaves, a foliated axis of a taxodiaceous conifer, and possible remnants of cycadophyte foliage.

Other Collections from the GSENM

According to Jeffrey Eaton (personal communication, 1997), about 60 sites in the Cenomanian Dakota Formation have yielded abundant well-preserved assemblages of fossil leaves potentially with cuticle preserved. These collections were sent to Dr. Jack Wolfe at the Denver U.S. Geological Survey (USGS), but apparently no work was done on the material before Wolfe's departure from USGS. Now it is unclear where the collections are housed. However, once recovered and studied, these collections will be important in showing how the Utah leaf assemblages compare floristically to those of similar age from the Dakota Formation in southeastern Nebraska (Upchurch and Dilcher, 1990). Results will add significantly to our understanding of mid-Cretaceous floral composition and document changes in the vegetation between the two areas. Additional fossil plant collections from the GSENM area are likely to be found in the paleobotanical collections at Brigham Young University, Utah Museum of Natural History, Weber State University, and other Utah educational institutions.

Research Potential and Direction

Based on present knowledge, the greatest research potential lies with the Cretaceous exposures of the Kaiparowits Plateau region. The Cretaceous especially is a significant time because it is during this interval that the flowering plants (angiosperms) first appear and undergo a major adaptive radiation, replacing and displacing many of the older Mesozoic cycads, cycadeoids, ferns, ginkgophytes, and coniferophytes. Although the angiosperms represent the dominant plant group with approximately 220,000 species in 300-400 families, the place and timing of their origin, as well as

the group(s) considered to be ancestral, remain topics of much research and debate. As pointed out by Gillette and Hayden (1997), the biota of this region may be unique due to the geographic restriction of the rock formations that comprise the Kaiparowits Plateau.

Therefore, it will be interesting to learn how the Cretaceous floras preserved in these rock units compare with similar-aged floras elsewhere in the western interior of North America. Further reconnaissance and monitoring of the Kaiparowits area undoubtedly will reveal additional plant-bearing localities.

Recommendations for Managing the GSENM Paleobotanical Resources

All paleobotanical resources within the Monument should be managed with the same care and consideration given to vertebrate fossils. At one point during the Symposium's paleontology discussions, some members of the public expressed concerns over no longer being able to collect fossil wood within the Monument. As discussed above, fossil woods are scientifically valuable, as they provide taxonomic, paleoecological, and paleoclimatic data about the woody components of ancient plant communities. Moreover, in some areas, fossil wood may be the only plant remains represented. Therefore, if future management plans call for opening up Monument sites for public collection of petrified wood, specimens from these areas should be first evaluated for their scientific value. This is especially the case in the Kaiparowits Plateau region where the potential for recovery of Cretaceous dicotyledonous woods is high. Fortunately, scientific study of fossil woods does not require collecting large samples, and therefore collecting is of relatively low impact to the environment. On the other hand, study of compression/impression floras does require, in many cases, that large collections be made to ensure adequate sampling. Consequently, the impact on the environment will be greater.

Also, from a management perspective, it is important to understand that plant parts can



get preserved in a number of different ways and that each preservational mode provides different types of information about the plant fossil (Schopf, 1975; Stewart and Rothwell, 1993). Furthermore, it is important to be aware that plant fossils may be found in all types of sedimentary rocks deposited in both terrestrial and marine environments. However, this is not to say that plant fossils will be found in every rock that is picked up. Although plant fossils most commonly occur as compressions and impressions in mudrocks and sandstones laid down in ancient lakes, swamps, deltas, and fluvial channels, ancient plant remains may also get preserved as three-dimensional permineralizations in limestones and chert deposits.

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Recommendations for Paleontological Research in the Grand Staircase-Escalante National Monument

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ABSTRACT

■ The extensive paleontological resources of several Cretaceous formations in the Grand Staircase-Escalante National Monument have been thoroughly investigated through systematic field work. Other formations, ranging in age from Permian to Quaternary, have been less intensively investigated for fossils, although some hold high promise for productive field investigations. Field recovery of fossils only begins the long process of paleontological research, which subsequently includes laboratory preparation, museum curation, identification, and analytical study. Paleontologists currently and recently active in the Monument should be encouraged to expand their field research in concert with other researchers, and to share their information with planning teams through publication of technical papers. For geological formations in the Monument that have not been thoroughly or recently investigated for fossils, researchers should be recruited to conduct field work and the full range of activities leading to completed research. Plans for curation and collection management should be established prior to extensive expansion of research on the paleontology of the Monument. Financial and logistic support will be critical to timely and successful paleontological research programs in the Monument. To the extent possible, specimens should be deposited in accredited museums. Educational activities that involve paleontological resources in the Monument will naturally follow successful execution of systematic research.

President Clinton cited outstanding paleontological resources in his proclamation that established the Grand Staircase-Escalante National Monument. Paleontology has been important in this region of Kane and Garfield Counties in southern Utah, most extensively in the past two decades. This report is a shortened and modified version of the more comprehensive assessment of paleontological resources in the Grand Staircase-Escalante National Monument published earlier last year by the Utah Geological Survey (Gillette and Hayden, 1997), and an expansion of the ideas presented by Gillette (1998), which provided basic recommendations for paleontological research in the Monument. Geological terminology follows that of Doelling (1975), Doelling and Davis (1989), and Allison (1997). Sources of paleontological information used to compile this report include published literature (see Selected

References in Gillette and Hayden, 1997), records contained in the Utah Bibliography of Paleontology database at the Utah Geological Survey, and unpublished information kindly supplied by researchers and curators of several institutions, including: Mr. Harley Armstrong (U.S. Bureau of Land Management); Dr. Sidney Ash (Weber State University); Dr. Brooks Britt (Museum of Western Colorado); Dr. Richard L. Cifelli (Oklahoma Museum of Natural History, University of Oklahoma); Dr. Jeffrey G. Eaton (Weber State University); Ms.



Janet Whitmore Gillette (Utah Museum of Natural History, University of Utah); Mr. James Jensen, Provo, Utah; and Mr. Kenneth Stadtman (Earth Science Museum, Brigham Young University).

The record of fossil animals and plants in the Grand Staircase-Escalante National Monument is extensive but uneven. Several geological formations of Cretaceous age, for example, the Kaiparowits Formation, have produced faunas and floras that today serve as global standards for comparison. Other formations in the Monument have not been as thoroughly investigated. For example, the Chinle Formation (Triassic) and the Morrison Formation (Jurassic) elsewhere have yielded important remains of dinosaurs and a wide variety of other organisms, but in the Monument, little systematic research has been conducted in these formations. Additional field work, laboratory work, and analytical research on all geological formations in the Monument will greatly improve the knowledge of the paleontology of this important region. To expand on the existing body of information concerning the paleontology of the Monument, a plan to review, test, evaluate, and study the fossil resources will be critical to the overall success of resource management.

Purpose and Goals

The U.S. Bureau of Land Management, the agency assigned to administer the Grand Staircase-Escalante National Monument, has begun to formulate a management plan that will include paleontology. Gillette and Hayden (1997) presented an overview of the state of knowledge in the Monument. That preliminary report had three goals: 1) to summarize existing knowledge of the paleontology of the Grand Staircase-Escalante National Monument, 2) to assess the potential for discovery of new and important paleontological resources, and 3) to recommend a plan that will address the need to more fully evaluate paleontological resources in the Monument.

The goal of this essay is to stimulate systematic planning for management of the fossils in the Monument. Although often opportunistic, the discipline of paleontology is executed most effectively with deliberation and planning, especially when management issues are principal concerns.

Stratigraphy

Sedimentary rocks, deposited over the past 256 million years, dominate the surficial geology of the Grand Staircase-Escalante National Monument (Doelling and Davis, 1989). The following summary identifies the most prominent geological formations for each of the three geological eras: the Paleozoic, Mesozoic, and Cenozoic. Gillette and Hayden (1997) and references therein provide a more elaborate review of the stratigraphy in the Monument.

Permian System (Late Paleozoic Era)

The oldest exposed rocks in the region are Permian in age and include the Hermit Shale, Coconino Sandstone, Toroweap Formation, White Rim Sandstone, and Kaibab Limestone. The sediments that comprise these formations originated in marine and shallow marine depositional environments.

Triassic System (Early Mesozoic Era)

Triassic rocks include the Moenkopi Formation (deposited in intertidal or shallow marine environments) and the Chinle Formation (stream deposits).

Jurassic System (Middle Mesozoic Era)

The Lower Jurassic Wingate Sandstone (massive dunes), Moenave Formation (stream and lake deposits), Kayenta Formation (stream and lake deposits), and the Navajo Sandstone



(massive dunes), are the oldest of the Jurassic formations.

The Middle Jurassic formations are the Page Sandstone and Carmel Formation (marine limestones, mudstones, and evaporites); and the Entrada Sandstone and Romana Sandstone, which are marginal marine sediments, evaporites, and massive dune fields.

The Morrison Formation represents the Upper Jurassic series, deposited as lake sediments, floodplain sediments, evaporites, dunes, mudflats, and stream sediments.

Cretaceous System (Late Mesozoic Era)

As much as 7,500 feet of Upper Cretaceous strata and 3,000 feet of Tertiary strata underlie the Kaiparowits Plateau. Upper Cretaceous strata include, in stratigraphic order (oldest to youngest), the Dakota, Tropic Shale, Straight Cliffs, Wahweap, and Kaiparowits Formations, and the lower part of the Canaan Peak Formation. The Dakota Formation, Tropic Shale, and Straight Cliffs Formation are exposed along the margins of the Kaiparowits Plateau, but are buried by younger strata in the central region. These sedimentary units were deposited under conditions ranging from shallow marine to terrestrial. The fossils found in the Cretaceous formations in the Monument reflect fluctuations in sea level during the waning stages of marine transgression in this part of the North American continent. They contain some of the most outstanding records of Mesozoic fossil mammals in the world.

Tertiary System (Cenozoic Era)

By early Tertiary time, regional tectonic activity and sea level changes had caused the final withdrawal of the shallow marine seaways. Volcanic activity in the region produced volcanic deposits that blanketed the area periodically, while rivers and streams eroded upland areas and deposited sediments in lowlands. Tertiary strata in the Monument include the upper part of the Canaan Peak Formation, the Pine Hollow and Wasatch (Claron)

Formations, and the overlying volcanic rocks of the Mount Dutton Formation and Osiris Tuff. Tertiary fossils have been found in the Claron Formation, but otherwise are not well known in the Monument.

Quaternary System (Late Cenozoic Era)

By the Quaternary Period, dating from approximately 1.8 million years ago to the present, the Colorado Plateau was elevated well above sea level, and tectonic activity in the Rocky Mountain region had produced massive mountain ranges in Utah and surrounding states. Fluctuating glacial conditions on the global scale resulted in alpine glaciers as far south as central Utah, with attendant fluctuations in climate that affected the entire continent. In the Monument, sediments that accumulated during this time include wind-blown sand; a variety of river and stream deposits including silt, sand, and gravel; and mass-wasting deposits such as landslides and talus debris. Basalts from nearby volcanic vents also accumulated in the Monument during the Quaternary, affecting drainage patterns and erosional conditions.

Paleontology

Most of the geological formations in the Monument contain fossils. Certain rock types, especially limestones and coal, are almost always richly fossiliferous. Because some formations crop out more extensively, or are more accessible, scientific coverage of the various formations in the Monument is uneven. Exposures are widespread, allowing access to most formations within the Monument. These exposures facilitate paleontological fieldwork. Paleontological studies have been conducted within the boundaries of the Monument and vicinity since the middle of the 19th century. The fossil record includes marine and terrestrial fossils that are critical for stratigraphic correlation, paleoenvironmental reconstruction, and study of the evolving faunas and floras.



Reports of fossils used for stratigraphy date back to the early part of the 20th century. Most of those published records are imprecise at best, precluding determination of exact locations where the fossils were found. In the past decade, paleontological research in the area now included in the Grand Staircase-Escalante National Monument has expanded dramatically. To the extent that the locality information is accurate and available, it is possible to summarize the knowledge of the paleontology of the Monument with a measure of confidence. Nevertheless, knowledge of the paleontology for all geologic formations in the Monument remains meager at best. Despite long lists of taxa that constitute the known biotas for each formation (Gillette and Hayden, 1997), most fossils have not been thoroughly studied, although paleontologists have recently contributed a considerable effort to improve that knowledge, especially in the Cretaceous formations.

Most of the formations that are exposed in the Monument are found elsewhere in Utah. Some extend throughout the Colorado Plateau and beyond. However, because of changing geographic conditions related to plate tectonics, the fossils in each formation in the Monument represent specific paleogeographic conditions. For example, the Morrison Formation, famous for its Jurassic dinosaurs, extends from central New Mexico to northern Montana, and from western Oklahoma to central Utah. Exposures of the Morrison Formation in the Monument are the westernmost occurrence of that formation; Morrison dinosaurs and other organisms found in the Monument are therefore the westernmost biota known for that formation. The Morrison biota in the Monument should reflect the influence of geography on the habitats, a subject that has not yet reached maturity in paleontological research. Paleontologists suspect that biotas were not uniform throughout the Morrison, but instead varied north to south, east to west, lowland to upland, and wet land to dry land. Conditions during the depositional history of the Morrison within the Monument were therefore different from conditions elsewhere in the Morrison

outside the Monument. Consequently, the biota represented by the fossils found in the Morrison Formation in the Monument is unique. Similar statements can be made for each formation in the Monument.

In contrast, several Cretaceous formations are known only from southern Utah, in particular the Straight Cliffs, Wahweap, and Kaiparowits Formations, all of which are exposed extensively within the Monument. Because of the extremely limited geographic extent of these formations, their biotas represent restricted and unique habitats and populations. Paleontologists have begun to study the fossils from these formations in earnest because of these unique conditions of limited geography and restricted populations.

Fossils from every formation in the Monument are important for a variety of reasons: 1) they represent the populations that lived in this area when the sediments in those formations were deposited; 2) they represent various habitats and geographic effects in the Monument that were influenced by tectonic activity and sea level changes; and 3) some represent highly restricted habitats and depositional conditions with unique biotas that are known only from southern Utah, especially from the Monument. The biotas in those formations are therefore unique and cannot be duplicated anywhere else.

Paleontological Record

Several of the geologic formations in the Monument are virtually barren of fossils, and in several others, the fossil record is sparse. In some formations, however, the fossil record is expanding rapidly, owing to considerable research that has been conducted in the area since the middle 1980's. Several of the Cretaceous formations have been studied with great intensity in recent years for the record of vertebrate life in this area. Mammals and dinosaurs are particularly important targets for this ongoing research, which has produced thousands of specimens that are housed in several major institutions.



Localities

Fossils occur broadly throughout the formations within the Monument (Gillette and Hayden, 1997). Most technical publications do not provide exact locality information. Most records in the Utah Geological Survey database are specific only to the level of township and range (roughly 36 square miles).

The list of fossil localities in Gillette and Hayden (1997) is certainly incomplete for two reasons: 1) paleontologists and their museums are generally reluctant to divulge exact locality information in print in order to protect the sites; and 2) fossils occur broadly throughout the formations, rather than only at isolated sites. Fossils found in one location may be expected elsewhere at the same stratigraphic horizon. Therefore, a specific fossil locality is a general indication of the fossil content of a formation at a certain stratigraphic position.

Selected Paleontological Resources by Geologic Formation

Gillette and Hayden (1997) presented a comprehensive overview of the fossil record for each formation in the Grand Staircase-Escalante National Monument, including extensive faunal and floral lists. Knowledge of the paleontology of these formations is uneven. Cretaceous formations have been studied with great intensity in the Monument and surrounding area, while formations of all other ages have been examined only cursorily as summarized below (Gillette 1998).

Example 1: Chinle Formation (Late Triassic)

Geologists working in the Monument and immediate vicinity have reported abundant carbonaceous material, logs of petrified wood, a palynological assemblage of 20 taxa, and extensive occurrences of fossil bones and plants. Very little of this record has been

studied systematically. The floral and faunal list spans a broad spectrum of fossils, including plants, petrified wood, snails, clams, fish, insects, horseshoe crabs, ostracodes, fish, reptiles, and tracks.

The plants and animals of the Chinle Formation represent terrestrial and freshwater habitats. Elsewhere (for example, the Petrified Forest National Monument, Arizona, and the Ghost Ranch area, New Mexico), the Chinle Formation has produced hundreds of taxa, including the oldest dinosaurs in North America and perhaps the world. The paleontology of the Chinle Formation in the Grand Staircase-Escalante National Monument has not been methodically studied. Exposures of this formation hold great promise for discovery of important plants and animals that constituted the biota that existed with the earliest dinosaurs. This formation deserves systematic field work in the Monument for its potential fossil content, especially dinosaurs and their relatives.

Example 2: Morrison Formation (Late Jurassic)

The list of confirmed fossils in the Morrison Formation in the Grand Staircase-Escalante National Monument and vicinity includes plants, dinosaurs, and other reptiles. None of these have been identified to even the genus level of classification. In essence, almost nothing is known about the fossils of this formation in the Monument.

Elsewhere, the Morrison Formation has produced the classic dinosaurs of the Jurassic Period (for example, *Allosaurus*, *Apatosaurus*, *Barosaurus*, *Brachiosaurus*, *Campotaurus*, *Ceratosaurus*, *Diplodocus*, *Seismosaurus*, *Siegosaurus*, *Supersaurus*, and many others). Dinosaurs and associated animals and plants from the Morrison Formation have become the world standard for Late Jurassic faunas and floras.

Faunal and floral lists from important sites such as Dinosaur National Monument typically include several hundred taxa of fish,



amphibians, reptiles (including dinosaurs), mammals, invertebrates, plants, pollen, and spores. Many of the most important sites in the Morrison Formation are in Utah and Colorado, but none are close to the Grand Staircase-Escalante National Monument. Unpublished records of dinosaur sites in this formation within the Monument indicate that it holds considerable promise for productive and important sites. Discovery of dinosaurs and associated fossils in the Monument will be critical to understanding the geographic and temporal variation of the Late Jurassic dinosaurs because of its geographic setting as the westernmost occurrence of the Morrison Formation in North America.

Example 3: Kaiparowits Formation (Late Cretaceous)

The Kaiparowits is the youngest of the Cretaceous formations in the Grand Staircase-Escalante National Monument. Pollen and spores, turtle shell fragments, dinosaur bones, mollusks, and plant fossils had been recognized in the Kaiparowits Formation prior to the 1980's. Until the past decade, little concentrated paleontological research in this formation was undertaken in the Grand Staircase-Escalante National Monument.

The Kaiparowits Formation in the Monument has been the focus of considerable attention by paleontologists since the middle 1980's. With 155 taxa, the fauna and flora of the Kaiparowits Formation are the most extensive Late Cretaceous biota in Utah, and one of the most important biota in North America. The biota includes a long list of pollen and spores, plants, clams, snails, sharks, skates, rays, bony fish, amphibians, turtles, lizards, crocodiles, dinosaurs, birds, and mammals.

The stratigraphic position of the Kaiparowits Formation, immediately preceding the major extinction episode at the end of the Cretaceous Period, is especially critical for the mammals in this formation. The fauna includes roughly 30 taxa of mammals, all of them small and ranging in size from that of

shrews to squirrels. The list includes some of the earliest marsupial mammals and true placental mammals in the world. These Cretaceous mammals immediately preceded the great expansion of Tertiary mammals following the extinction of the dinosaurs. Research on the habitats and paleobiological setting of the terrestrial animals and plants of the Late Cretaceous is presently the object of considerable effort within the Monument.

Recommendations for Paleontological Research

Successful management of the paleontological resources in the Grand Staircase-Escalante National Monument will require expansion of knowledge of the fossils in this area. Additions to that body of knowledge will necessarily involve verification of known resources and a comprehensive effort to identify new resources, particularly in formations that have not been sufficiently studied in the Monument.

Field recovery of fossils is the first step in recognition of new resources. The long process of documentation, which only begins with the initial field recovery, requires field documentation, laboratory preparation of the specimens for museum curation, accessioning of the specimens, and associated documentation into a museum collection, identification, and analytical study. A general rule of thumb for basic paleontological research with a field emphasis, as recommended here, is the "Rule of Ten": for every hour of field time, at least 10 hours of lab and curation time will be required prior to release for analytical research. Similarly, 10 days of field work will commonly require 100 days of laboratory and curation. These followup activities are commonly low profile and not generally conducted in the public domain, but they are essential for responsible research. Budgets and schedules for management and research projects should be adjusted to accommodate these constraints.



Although paleontologists are generally interested in the formations within the Monument, only a few paleontologists presently have specific interests within the boundaries of the Monument. For those formations that have been understudied and underexplored within the Monument, paleontologists should be recruited for specific research projects that will increase knowledge of paleontology in this area. Paleontologists already working on projects within the Monument should be encouraged to continue their research and participate in management decisionmaking processes. To assure cooperation of these paleontologists, certain security measures should be considered: protection of sites, protection of site information, protection of the fossils collected as well as those still in situ, and long-range plans to continue their research programs without interference. In all cases, existing projects should be honored and allowed to mature.

Collection management should be considered prior to commencement of paleontological research in the Monument. All specimens and associated data should be deposited in an accredited museum by prior agreement between the researcher and the selected museum. Educational opportunities that arise from paleontological research will follow naturally from these activities. The most common educational benefit of paleontological research is the accumulation of display specimens, but equally important opportunities for community involvement, such as volunteer activities and school field trips, should also be explored.

Conclusions

Fossils occur throughout the Grand Staircase-Escalante National Monument. The paleontological record for several formations has been recognized in recent years as worthy of considerable research for purposes of stratigraphic correlation, understanding changing paleobiological conditions on the land and in the sea, and understanding the evolution of plants and animals during the waning stages of

the reign of dinosaurs in North America in the Cretaceous Period. Additional research should be directed toward Triassic and Jurassic formations, which have high potential for critical discoveries relating to the origin and radiation of dinosaurs, and Quaternary sediments, which probably contain mammoths and their associated floras and faunas.

Knowledge of the paleontology of all the formations in the Monument is still rudimentary, as indicated by the recent intensified interest in the fossils of the Monument and vicinity. For all formations, field work, museum curation, and laboratory analysis are essential.

Comprehensive Plan

A comprehensive plan to identify and study fossils in the Grand Staircase-Escalante National Monument should be organized to amplify knowledge of the prehistoric life of all formations that have fossils. Execution of the plan must extend beyond simple inventory of sites to include the following aspects:

Preliminary analysis

- Literature research, database review, and communications with active researchers
- On-the-ground prospecting and sampling
- Specimen preparation and curation of samples in appropriate museums
- Evaluation of the samples and prospecting results

Excavation

- Excavation of selected important localities
- Laboratory preparation of excavated specimens
- Curation in accredited museums
- Research and publication by specialists as appropriate
- Final evaluation of sites and formations for their fossils
- Assessment of long-term potential for additional production of important specimens
- Assessment of scientific and educational values
- Recommendations for mitigation



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Larger Vertebrates of the Kaiparowits Formation (Campanian) in the Grand Staircase-Escalante National Monument and Adjacent Areas

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The Kaiparowits Formation comprises more than 800 meters of the more than 2,000-meter-thick sequence of Cretaceous rocks exposed on the Kaiparowits Plateau. This formation is the most fossiliferous and youngest-vertebrate-bearing of these Cretaceous units. It records an interval in which rocks and fossils were deposited by large rivers with broad alluvial floodplains (Eaton, 1991). Exposures of the Kaiparowits

ABSTRACT

■ The Kaiparowits Formation of south-central Utah contains a long (about 800-meter) section of nonmarine sediments of Campanian age. Vertebrate fossils are found throughout the unit, but the lower vertebrate fauna has not been thoroughly sampled. Taxa of larger lower vertebrates recognized thus far include eight turtles, two crocodilians, nine dinosaurs, and one bird. The large vertebrates indicate a closer similarity to Campanian faunas of New Mexico and Texas than to those of Montana and northward. All of the southern faunas of this age are, however, rather poorly known in comparison with the rich faunas of the Judith River and Two Medicine Formations to the north.

Formation occur primarily within the area contained within the boundaries of the Grand Staircase-Escalante National Monument, although important exposures also occur within Dixie National Forest and on private lands along the northern border of the Monument.

Although vertebrates had been noted from the Kaiparowits Formation by several workers (see Cifelli 1990a for references), most of our knowledge of vertebrates from this unit has resulted from work begun in the early 1980's by parties led by Richard Cifelli (then at the Museum of Northern Arizona and later Oklahoma Museum of Natural History) and Jeffrey Eaton (then at the University of Colorado, Boulder, and more recently collecting for the Utah Museum of Natural History). They began prospecting and screen washing for microvertebrates, with research focusing on uncovering the history of early mammalian



faunas. The results of this work in expanding the mammalian fauna of the formation was last summarized by Eaton and Cifelli (1988), and detailed studies of the mammals have appeared more recently (Cifelli, 1990a, b; Cifelli and Eaton, 1987; Cifelli and Johanson, 1994; Cifelli and Madsen, 1986; Eaton, 1987). By contrast, the lower vertebrate faunas of the Kaiparowits Formation have received less attention. Hutchison (1993) reported on the discovery of the enantiornithine bird *Avisaurus*, and Parrish and Eaton (1991) presented a discussion of the dinosaur faunas, both in abstracts. Collaborative field work since 1993 conducted by Jeffrey Eaton and J. Howard Hutchison (University of California Museum of Paleontology, Berkeley) made a concerted effort to enhance our knowledge of lower vertebrates from the formation. Most recently, Gillette and Hayden (1997) compiled available data from publications and government documents, and Eaton et al. (in press) summarize the entire fauna based on unpublished studies, museum research, and previously published reports. The records of lower vertebrates summarized here are abstracted from Eaton et al. (in press).

Mammalian correlations (Eaton and Cifelli, 1988) and pollen and spores (Nichols, 1997) indicate a Campanian age (Late Cretaceous, approximately 72 to 83 million years ago) for the Kaiparowits Formation. Elsewhere in North America, the evolution of terrestrial faunas in this time period is principally represented by the fossils of the Fruitland Formation in New Mexico, the Aguja Formation in west Texas, the Two Medicine Formation in Montana, and the Judith River Formation as exposed in eastern Montana, western North Dakota, and southern Alberta Province in Canada. Thus, the Kaiparowits Formation serves as an important biogeographic link for this time period between these better-known areas.

Fossils occur most commonly as lag in the sandstones associated with rivers and in mudstones associated with floodplain and paludal environments. They are somewhat more

common in the lower half of the formation than in the upper part, although there is no significant difference in the faunas found in the upper and lower part of the sequence (Eaton and Cifelli, 1988). Fossils occur at low frequency throughout the formation and are routinely exposed through erosion. No "bone beds" or areas of high abundance have yet been identified; most localities represent spot occurrences (e.g., a partial, associated specimen), slightly larger areas or horizons where samples for screening have been taken, or yet larger areas (on the order of 100 meters squared) where unassociated, dispersed elements of many animals are found.

Knowledge of the microherpetofauna (e.g., snakes, lizards, and amphibians) comes principally from sites at which tons of matrix have been sieved under water and the residues carefully picked under microscopes. Our understanding of larger vertebrates (e.g., many fish, turtles, crocodiles, dinosaurs, and birds) comes primarily from fossils collected as surface float recovered during careful reconnaissance. Sampling of the Kaiparowits Formation by either technique is still in its early, exploratory phase. Much of the topography of the area in which the Kaiparowits Formation is exposed is steep and road access is limited. Thus, a more complete knowledge of the fauna will require many years of additional exploration.

Lower Vertebrate Fauna

Lower vertebrates (Tables 1 and 2) collected from the Kaiparowits Formation reside in several institutions, with the major collections at the University of Colorado in Boulder, Oklahoma Museum of Natural History in Norman, Museum of Northern Arizona in Flagstaff, Utah Museum of Natural History in Salt Lake City, Brigham Young University in Provo, Utah, and the University of California Museum of Paleontology in Berkeley. Taxa represented in the University of California collections and seen by the Berkeley authors are indicated by an asterisk (*).



Table 1. Comparison of larger lower vertebrates from Campanian formations in western North America: the Judith River Formation (JRF) in Saskatchewan, Alberta, and Montana; the Two Medicine Formation (TMF) in Montana; the Fruitland Formation (FF) in New Mexico; the Aguja Formation (AF) in Texas; and the Kaiparowits Formation (KF) in Utah. Published data (Armstrong-Ziegler, 1980; Eaton et al., in press; Gordenier et al., 1995; Gilllette and Hayden, 1997; Hutchison and Archibald, 1986; McCord, 1996, 1998; Parrish and Eaton, 1991; Rowe et al., 1992; Weishampel, 1990) was supplemented by personal observations. An "x" indicates a record; numbers indicate number of species recognized.

TAXA	JRF	TMF	FF	AF	KF	TAXA	JRF	TMF	FF	AF	KF
TURTLES						Elmidae					
Boenidae						Chirostenotes					
<i>Baemys</i>	x	-	-	-	x	<i>Elmidae</i>	x	-	-	-	-
<i>Plesiochelys</i>	x	-	-	-	-	Caenagnathidae					
" <i>Baemys</i> "	x	-	x	x	x	<i>Caenagnathus</i>	2	-	-	-	-
Neurankylidae						Troodontidae					
<i>Neurankylus</i>	x	-	x	-	x	<i>Troodon</i>	x	x	-	cf.	-
Adocidae						Dromaeosauridae					
<i>Adocus</i>	x	-	x	x	x	<i>Dromaeosaurus</i>	x	x	-	cf.	-
Nanhsiungchelyidae						<i>Saurornitholestes</i>	x	x	-	cf.	-
<i>Basilemys</i>	x	-	x	x	x	Segnosauria					
Kinosternia						<i>Erlasaurus</i>	cf.	-	-	-	-
new genus	-	-	-	-	x	Ornithischia					
<i>Haplachelys</i>	-	-	-	cf.	-	Hypsilophodontidae					
Trionychidae						<i>Thescelosaurus</i>	x	-	-	-	-
<i>Apalone</i>	x	-	-	-	-	<i>Orodromus</i>	-	x	-	-	-
<i>Aspideretides</i>	x	-	-	-	-	Hadrosauridae					
" <i>Aspideretides</i> "	-	-	x	x	x	<i>Brachylophosaurus</i>	x	-	-	-	-
Chelydridae						<i>Gryposaurus</i>	x	-	-	?	-
<i>Macrobaenidae</i>	x	-	-	-	-	" <i>Kritosaurus</i> "	x	-	-	-	-
Pleurasternidae						<i>Prosaurolophus</i>	x	-	-	-	-
<i>Compsemys</i>	-	-	x	-	x	<i>Malasaurus</i>	?	x	-	-	-
CROCODILES						<i>Corythosaurus</i>	x	-	?	-	-
Ganiaphalidae						<i>Lobosaurus</i>	2	-	-	-	-
Alligatoroidea						<i>Parasaurolophus</i>	x	-	-	-	x
<i>Brachychampsa</i>	-	-	-	-	x	Pachycephalosauridae					
<i>Albertachampsa</i>	x	-	-	-	-	<i>Stegoceras</i>	x	-	-	x	x
<i>Leidyosuchus</i>	2	-	-	-	-	<i>Gravithalus</i>	x	x	-	-	-
Crocodylidae						<i>Pachycephalosaurus</i>	x	-	-	-	-
<i>Tharacosuchus</i>	-	-	x	-	-	<i>Ornatolithus</i>	x	-	-	-	-
Eusuchia indet.						Protoceratopsidae					
<i>Deinosuchus</i>	-	-	-	x	-	<i>Protoceratops</i>	-	-	-	-	x
DINOSAURS						Ceratopsia					
Saurischia						<i>Anchiceratops</i>	2	-	-	-	-
?Carnosauria						<i>Chasmosaurus</i>	3	x	?	x	-
<i>Aublysodon</i>	x	x	-	-	-	<i>Monoclonius</i>	x	-	-	-	-
Tyrannosauridae						<i>Centrosaurus</i>	x	?	-	-	-
<i>Albertosaurus</i>	2	x	?	-	cf.	<i>Styracosaurus</i>	x	x	-	-	-
<i>Daspletosaurus</i>	x	-	-	-	-	<i>Brachyceratops</i>	-	x	-	-	-
Ornithomimidae						<i>Pentaceratops</i>	-	-	x	-	-
<i>Struthiomimus</i>	x	-	-	-	-	Nodosauridae					
<i>Dromiceomimus</i>	x	-	-	-	-	<i>Nodosaurus</i>	-	-	-	-	?
<i>Ornithomimus</i>	x	-	cf.	-	x	<i>Edmontonia</i>	2	x	-	x	-
						<i>Panoplosaurus</i>	x	-	-	-	-
						Ankylosauridae					
						<i>Euoplocephalus</i>	x	x	-	-	x



Table 2. Uncritical list of the lower vertebrates of the Kaiparowits Formation compiled from personal observations and published lists and descriptions (see Table 1).

Class Chondrichthyes	Family Adocidae
Order Hybodontiformes	Adocus sp.
Family Hybodontidae	Family Trianychidae
Hybadus sp.	cf. "Aspideretes" sp.
Family Polyacrodontidae	Family Nanhshungchelyidae
Lissodus sp.	Basillemys veriolasa (Cope, 1876)
Order Rajiformes	Family incertae sedis
Family Sclerorhynchidae	Naomichelys sp. [error - not known from this formation]
Ischyroza sp.	Family Chelydridae indet.
Family Rhynobatidae	Order Squamata
Myledaphus bipartitis Cope, 1876	Family Teiidae
Order Orectalobiformes	Chamops segnis Marsh, 1892
Family Brachaeluridae	Leptochamops denticulatus (Gilmore, 1928)
Brachaelurus? sp.	Meniscognathus altmani Estes, 1969
Family ?Ginglymostomatidae	Paraglyphanodon gazini Gilmore, 1943
Squatirhina sp.	cf. Polyglyphodon n. sp.
Class Osteichthyes	Family Anguillidae
Order Semionotiformes	Odaxsaurus piger (Gilmore, 1928)
Family Lepisosteidae	cf. Odaxsaurus n. sp.
Lepisosteus sp.	Anguillidae n. gen. & sp.
Order Amiiformes	Family Xanasauridae
Family Amiliidae	Exostinus sp.
Amia sp.	Family Parasaniwidae
Melvis sp.	Parasaniwa wyomingensis Gilmore, 1928
Order Elopiformes	Parasaniwa sp.
Family ?Phyllodontidae	Family ?Helodermatidae indet.
Paralbula sp.	Family incertae sedis
Order Perciformes	Litakis sp.
Family Palaeoalbulidae	Suborder Serpentes indet.
Palaeoalbulus sp.	Order Crocodylia
Order Acipenseriformes	Family Bernissartidae
Family Acipenseridae	Bernissartia sp. [identification questioned here]
Acipenser sp.	Family Crocodylidae
Order Elapiformes	Brachychampsa sp.
Family Elopidae indet.	Family Goniaphalidae indet.
Class Amphibia	Subclass Dinosauria
Order Urodela	Order Saurischia
Family Prosirenidae	Family Dromaeosauridae
Albonerpeton sp. cf. A. nexuosus Estes, 1981	Velaciraptorinus indet.
Albonerpeton sp.	Dromaeosaurinae indet.
Family Scapherpetantidae n. gen. & sp.	Family Troodontidae
Family Sirenidae	Troodon sp.
Habrosaurus dilatus Gilmore, 1928	Family Ornithimidae
Order Anura	Ornithimimus velox Marsh, 1890
Family Discoglossidae	Family Tyrannosauridae indet.
Scotophryne pustulosa Estes, 1969	cf. Albertosaurus sp.
Family Pelobatidae	Order Ornithischia
Eopelobates sp.	Family Nadasauridae
Class Reptilia	Family Ankylosauridae
Order Chelonio	Euoplocephalus sp.
Family Baenidae	Family Hadrosauridae
Baemys pulchra Lambe, 1906	Parasauralaphus sp. cf. P. cyrtocristatus Ostrom, 1961
Baena nodosa Gilmore, 1916	Family Pachycephalosauridae
Family Pleurosternidae?	Stegoceras sp.
Camptemys victa Leidy, 1856	Family Ceratopsidae indet.
Order Chelonio	Class Aves
Family Neurankylidae	Order Enantiornithiformes
Neurankylus eximius Lambe, 1902	Family Avisauridae
Superfamily Kinasternoidea n. gen. & sp.	Avisaurus n. sp.



The strictly aquatic component of the fauna is represented principally by fish. Gars (*Lepisosteidae**) are often represented by scales; two types of amiiformes (the bowfins - cf. *Amia* and *Melvinia**), a paleolabrid perch, and at least two elopimorphs (ten punders) are also known. Sharks are rare and are known from only a single locality near the base of the formation (Eaton and Cifelli, 1988).

Amphibians and squamate reptiles are treated elsewhere (Gillette and Hayden, 1997; McCord, 1996, 1998; Eaton et al., in press).

Chelonians (turtles) are the most commonly encountered lower vertebrate in surface collections, comprising at least nine genera arrayed over eight families. The pleurosternid *Compsemys** from the Kaiparowits and underlying Wahweap Formation represents the earliest record of this derived pleurosternid (Hutchison, 1987). The genus is not found in the Campanian formations to the north (Table 1). This rather small, carnivorous, and probably paludal turtle is relatively common. *Adocus** (*Adocidae*) is a common, large, probably herbivorous, aquatic turtle reaching up to 750 mm in shell length. The trionychids (soft-shelled turtles) are represented by probably more than one taxon of the "*Aspideretes*" type,* possibly referable to *Aspideretoides* (Gardener et al., 1995). Trionychids are highly aquatic turtles that occupy a variety of riverine and lacustrine environments and are probably the most common turtles found in the formation. The extinct family Baenidae is represented by at least two genera ("*Baena*" *nodosa** and *Boremys**). Baenids are most common in the channel deposits indicating preference for main river environments. *Basilemys variolosa** (*Nanhsiungchelyidae*) is relatively rare in the formation. *Nanhsiungchelyids* are large terrestrial herbivores resembling modern land tortoises (*Testudinidae*) in general features, but these characteristics were derived independently in this extinct family. *Basilemys* is among the largest of the turtles in the formation reaching lengths of up to 780 mm in shell length. The extinct *Neurankylidae* are relatively common large riverine turtles that reach a shell length of 870 mm and are represented by

Neurankylus eximius.* The Chelydridae* (snapping turtles) are relatively rare in the Kaiparowits Formation. These bottom walking, aquatic, and carnivorous turtles are relatively small, about the size of, or less, than that of the modern snapping turtle (*Chelydra*). The mud turtles (*Kinosternia**) are represented by isolated elements, mostly in mudstone deposits indicative of relatively quiet waters. The taxon in the Kaiparowits Formation represents a new genus and is the earliest known member of this group of small carnivorous turtles (carapace length of less than 150 mm).

Crocodylians are represented by two or more genera. A large goniopholid* (total length about 5 meters or more) is represented only by fragmentary specimens. Alligatorids are represented by much of a skull of a small *Brachychampsa** similar to *B. sealeyi* from the Menefee Formation of New Mexico (Williamson, 1997). The listed record (Gillette and Hayden, 1997) of the Bernissartidae, *Bernissartia* sp., has not been seen by the first author and may represent a misidentified *Brachychampsa*.

Dinosaur fragments are common in the Kaiparowits Formation, but well-preserved specimens identifiable to species are rare. Most records to date consist of teeth, toe bones, or small skull fragments. Many of these remain to be documented by detailed descriptions or published voucher specimens (Gillette and Hayden, 1977; Eaton et al., in press).

The order Saurischia is represented by the Dromaeosauridae* (*Velociraptorinae* indet. and *Dromaeosaurinae* indet.), Troodontidae (*Troodon*), Ornithomimidae (*Ornithomimus velox**), Tyrannosauridae (cf. *Albertosaurus**). The *Ornithomimus* is the most complete saurischian found thus far in the formation and consists of vertebrae, parts of the pelvis, and much of the hind limbs (De Courten and Russell, 1985). Carnivorous dinosaurs are more commonly represented by the birdlike ornithomimids rather than by tyrannosaurs, which are more common in the Judith River Formation. The records of *Paronychodon* and *Struthiomimus* listed by Gillette and Hayden (1997) are in need of critical evaluation.



The Ornithischia are represented by the Notosauridae and Ankylosauridae (*Euoplocephalus**), Hadrosauridae (duckbills) (*Parasaurolophus* cf. *P. cyrtocristatus**), Pachycephalosauridae (*Stegoceras**) and Ceratopsidae.* The record of cf. *Triceratops* reported in Gregory and Moore (1931) is based upon a vertebra and is not generically assignable. *Parasaurolophus* is the most complete ornithischian found thus far and consists of a substantial part of the skull, including the crest. Of the two generically identified hadrosaur fossils in the Kaiparowits Formation, both belong to *Parasaurolophus*, a genus that is exceedingly rare elsewhere.

The only bird found in the formation represents a new species of *Avissaurus* (Avisauridae) and is the most complete skeleton of an enantiornithiform bird from North America.

Comparisons With Other Campanian Faunas

Given the good to high quality of preservation evinced by the fossils of the Kaiparowits Formation, the level of diversity of the mammalian faunas, and the considerable exposure of the formation within the Monument, we should expect to find a highly diverse fauna of lower vertebrates in this area. However, comparisons with the Campanian faunas of other areas in North America clearly demonstrate that the lower vertebrate fauna of the Kaiparowits Formation still remains largely undersampled (Table 1). Our discussion is based on comparisons with published lists and on our own observations of unpublished museum collections.

Carnosaurs (meat-eating dinosaurs) are represented primarily by a greater abundance of smaller-bodied ornithomimids than with the larger tyrannosaurs, known only from a few teeth. A reverse ratio is found in the Judith River Formation. Ornithischians are particularly underrepresented in the Kaiparowits Formation. Several families of dinosaurs

(Hypsilophodontidae, Elmsauridae, Caenagnathidae, Protoceratopsidae) are unknown in the Kaiparowits Formation. Ceratopsians and pachycephalosaurs are rare in comparison with northern faunas.

Birds, known only from two specimens of the enantiornithine *Avissaurus*, are the most clearly undersampled. Although avian remains are typically rarer than those of other vertebrates, entire groups known elsewhere in the Cretaceous (e.g., hesperornithiformes) are not yet represented in collections from southern Utah.

Despite the fact that much of the lower vertebrate fauna is still to be found, some distinct faunal differences from other Campanian faunas can already be discerned. On average, the chelonians of the Kaiparowits Formation are similar in terms of diversity, but larger in body size than their more northerly representatives in the Judith River Formation. Some turtles (*Compsemys*, "*Baena*," and the small mud turtle) are not represented in the northern faunas, while others are absent from the southern faunas. The eosuchian *Champsosaurus*, relatively common in the Judith River Formation, is not known in Utah.

Of the dinosaurs at generic level of identification or above, all are found in the Campanian formations to the north (Montana, Alberta, and Saskatchewan) (Table 1). The diverse dinosaurs and crocodilians are particularly underrepresented in the Kaiparowits Formation. Ceratopsians and pachycephalosaurs are also rare in comparison.

Comparisons with the more southerly Campanian faunas from the Kirtland Formation in New Mexico and the Aguja Formation in the Big Bend area of Texas (Table 1, Figure 1) show that these faunas, while marginally similar in diversity to the Kaiparowits fauna, are also undersampled. Considering the short history of collecting in the Kaiparowits Formation compared with the other faunas, this formation is likely to yield one the more diverse assemblages when adequately sampled.

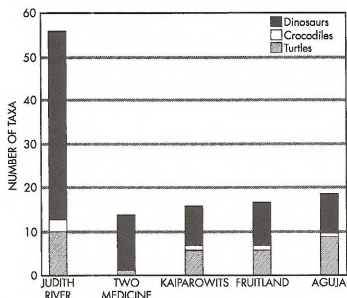


Figure 1. Summary of data presented in Table 1 with the Campanian formations from north to south arranged from left to right. Note the comparatively limited number of dinosaurian taxa currently known from the more southern faunas.

Conclusions

The Kaiparowits Formation in southern Utah partly bridges a large geographic gap in our knowledge of Campanian lower vertebrate faunas between the well-known faunas of Montana and Canada and the less well-understood faunas of New Mexico and Texas (Table 1, Figure 1). The very imperfect knowledge of the lower vertebrates suggests differences in faunal composition in both taxonomic diversity and relative abundance, perhaps reflecting a less marine-influenced and better-drained environment. The turtle, crocodilian, and dinosaur fauna indicates a predictably closer similarity to that of the New Mexican and Texas faunas, but the precise nature of this similarity is far from understood either temporally, environmentally, or taxonomically. The increase in body size of the turtles among taxa shared with the northern and southern faunas indicates warmer climates as with the southern faunas.

Future work in the well-developed exposures of the Kaiparowits Formation within the Grand Staircase-Escalante National Monument promises to provide us with a uniquely

well-balanced window to Campanian faunas in the southern United States. The continued application of screen-washing techniques, coupled with surface reconnaissance, will allow the recovery of both the smallest and largest elements of this important fauna and national resource.

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Late Cretaceous Microherpetofaunas of the Kaiparowits Plateau, Utah: Paleobiogeography and Paleoecology

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ABSTRACT

■ At least 22 genera in 16 families of small reptiles and amphibians have been recovered from the Dakota, Straight Cliffs, Wahweap, and Kaiparowits Formations on the Kaiparowits Plateau, ranging in age from Cenomanian through Campanian. These fossils are significant for three reasons: 1) microherpetofaunas are poorly known in southern Cretaceous localities of the West, 2) microherpetofaunas are poorly known from before the late Campanian (Judithian) of North America, and 3) the Kaiparowits Plateau affords a picture of the changes in the microherpetofauna in one area from Turonian throughout Campanian. These faunas include widespread Mesozoic forms, typical southern forms such as the polyglyphanodontines, and unique forms such as a new genus of polyglyphanodontine lizard. The occurrence of polyglyphanodontine lizards in the Kaiparowits region reinforces the notion that they are a typical component of the western portion of the "southern community" during the late Cretaceous. The early occurrence (Turonian) of *Paraglyphanodon* here raises the possibility that the subfamily was widespread in the poorly documented early Late Cretaceous, accounting for the subfamily's Asian-Western North American distribution.

The Kaiparowits Plateau of south-central Utah includes Cretaceous sediments spanning six formations of Cenomanian through Campanian age. Four formations, the Dakota, the Straight Cliffs, Wahweap, and Kaiparowits, have produced small reptile and amphibian fossils included in this study (Table 1). The Cretaceous sediments deposited in the Kaiparowits basin consist of intertonguing continental and marine beds. The beds were deposited during widespread transgressions and regressions of the Western Interior Sea to the north (Lessentine, 1965; Elder and Kirkland, 1993).

The small reptiles and amphibians of the Cretaceous system in this region are of significance for three reasons. First, the microherpetofauna is poorly known from southern

Cretaceous localities in the west. Previous southern faunas have been reported from the Fruitland Formation of the San Juan Basin, New Mexico (Armstrong-Ziegler, 1978, 1980; Sullivan, 1981), the Aguja Formation of Texas (Rowe, et al., 1992), and the Comanche Series of Texas (Winkler, et al., 1990). One or two taxa have also been reported from: the North Horn Formation of Utah (Gilmore, 1940, 1942, 1943); the Cedar Mountain Formation of Utah (Cifelli and Nydam, 1995); the "El Gallo Formation" of Baja California del Norte, Mexico (Estes, 1983; Estes and Sanchiz,

**Table 1.** Small reptiles and amphibians from the Cretaceous of the Kaiparowits Plateau.

	Dakota	Straight Cliffs		Wahweap	Lower Kaiparowits	Upper Kaiparowits
		Smokey Hallow	John Henry			
Class Amphibia						
Order Caudata						
Family Proseriidae						
<i>Albanerpeton</i>		X	X		X	
Family Batrachosauroididae						
<i>Ophisthotriton</i>					X	
<i>Prodesmodon</i>					X	
Family Scapherpetonidae						
<i>Lisserpeton</i>					X	
<i>Scapherpeton</i>					X	
Family Sirenidae						
<i>Habrosaurus</i>					X	X
Order Anura						
Family Discoglossidae						
<i>Scaphophryne</i>		X			X	X
Family Pelobatidae						
<i>Eopelobates</i>		X			X	X
Class Reptilia						
Order Squamata						
Family Teiidae						
<i>Chamops</i>				X	X	X
<i>Lepidochamops</i>	X				X	
<i>Paraglyphadon</i>			X			
<i>New polyglyphadontine</i>					X	X
Family Xenosauridae						
<i>Exostinus</i>					X	
Family Anguidae						
<i>Odaxosaurus</i>		X	X	X	X	X
Taxon A					X	
Taxon B					X	
Family Necrosauridae						
<i>Parasaniwa</i>						
Family Helodermatidae					X	
Family Varanidae					X	
<i>Paleosaniwa</i>				X		
Family Boidae					X	

1982); and, the Packard Formation, Sonora, Mexico (Lucas, et al., 1995).

Next, the microherpetofaunas from the Cretaceous of western North America before the late Campanian (Judithian) are even more poorly known. Essentially, reports are limited to faunas of the Aptian-Albian Comanche Series of Texas (Goin and Auffenberg, 1958; Fox and Naylor, 1982; Winkler, et al., 1990) and to the early Campanian (Aquilan) Milk River Formation of Alberta, Canada (Russell,

1964; Naylor, 1979; Fox and Naylor, 1982; Gao and Fox, 1991; Gao, 1992).

Lastly, the Kaiparowits Plateau in this study affords a picture of the changes in the microherpetofauna in one area from Turonian through Campanian.

Geological Setting

Sediments of the Cretaceous system are represented in the Kaiparowits Plateau by, from oldest to youngest, the Dakota, Tropic Shale, Straight Cliffs Sandstone, Wahweap Sandstone, Kaiparowits, and Canaan Peak Formations. Fossils recovered in this study were from the Dakota, Straight Cliffs, Wahweap, and Kaiparowits Formations.

The Dakota Formation in this region has been divided into three informal members: a lower conglomeratic member, a middle carbonaceous member, and an upper member representing the initial transgression of the Greenhorn Sea (Peterson, 1969a). Vertebrate fossils have been recovered from the middle member (Cifelli and Madsen, 1986; Eaton, 1987a). The age of the middle member has been determined, on the basis of palynomorphs, to be Cenomanian (Agasie, 1969; May and Traverse, 1973;



am Ende, 1987). In addition, marine mollusks recovered from the upper member are of late Cenomanian age (Peterson, 1969a).

The Straight Cliffs Formation overlies the latest Cenomanian to middle Turonian marine beds of the Tropic Shale, which in turn overlies the Dakota Formation (Peterson, 1969a). Four members have been named (Peterson, 1969b), comprising approximately 500 m of section. In ascending order, they are the Tibbet Canyon Member, the Smoky Hollow Member, the John Henry Member, and the Drip Tank Member.

The Tibbet Canyon Member consists of over 30 m of section, in the type area, of cliff-forming sandstones deposited in a beach and shallow-water, regressive marine environment. Marine invertebrates recovered from this section suggest an age of middle Turonian (Peterson, 1969b).

The Smoky Hollow Member also consists of over 30 m of section, in the type area, of sandstones, mudstones, and coal, deposited in a fluvial-floodplain, lagoonal, and paludal environment. The age of the Smoky Hollow Member is constrained by the age of the underlying Tibbet Canyon Member (middle Turonian) and the overlying John Henry Member (early Coniacian) (Peterson, 1969b). A regional unconformity of unknown duration separates the Smoky Hollow Member from the overlying John Henry Member.

The John Henry Member consists of over 200 m of section, in the type area, of sandstone, mudstone, and coal, deposited in both marine and nonmarine environments (Peterson, 1969b). Marine invertebrates recovered from the basal John Henry Member contain an early Coniacian fauna (Eaton, 1987a). The top of the John Henry Member is assigned an upper Santonian age based on marine mollusks (Eaton, 1987a). Most of the localities have been referred to the Santonian; however, one (HC2) may be low enough to be Coniacian in age (Eaton and Cifelli, 1988).

The Drip Tank Member consists of almost 50 m of section, in the type area, of cliff-forming sandstone, deposited in a fluvial environment. The basal Drip Tank Member probably interfingers with the top of the John Henry Member, and therefore, is inferred to be of only slightly younger age (Peterson, 1969b).

The Wahweap Formation overlies and interfingers with the Drip Tank Member of the Straight Cliffs Formation (Peterson, 1969b). The Wahweap Formation consists of siltstones, mudstones, and massive sandstones, and is characterized, in part, by the absence of coal (Gregory and Moore, 1931). Informal lower, middle, upper, and capping sandstone members have been proposed (Eaton, 1987a). Depositional environment for most of the formation has been interpreted as interbedded, braided belt tongues, typical of alluvial plain facies, with the mudstones in the basal portion of the unit, representing local lacustrine environments (Peterson et al., 1980). As the depositional environment was entirely terrestrial, dating is not well-constrained. Palynomorphs from the correlative Masuk Formation suggest an early Campanian Age (Peterson et al., 1980; Eaton, 1987a). Comparison of mammals recovered from the formation (Eaton and Cifelli, 1988; Cifelli, 1990a, b) suggest an Aquilian faunal "stage" (Russell, 1964) or Land Mammal age (Lillegraven and McKenna, 1986) and, hence, early Campanian age.

The Kaiparowits Formation consists of 850 m of siltstones and mudstones deposited in meandering river and associated floodplain deposits (Eaton, 1987a). Palynomorphs recovered from the formation have been interpreted as representing Maastrichtian age (Lohrengel, 1969a, b), or more convincingly, a Campanian age (Bowers, 1972; Eaton, 1987a). Mammalian fossils recovered from the formation are consistent with a Judithian faunal "stage" (Russell, 1964) or Land Mammal age (Lillegraven and McKenna, 1986), which has been interpreted variously as Campanian-Maastrichtian boundary (Lillegraven and McKenna, 1986) or as Campanian (Eaton, 1987b) in age. One locality, TB8, is located approximately 200 m higher



than other localities, so it is treated separately as the "upper fauna" with the remainder being the "lower fauna."

Paleobiogeography and Paleocology

This section reviews the fossil flora and fauna from the relevant formations of the Kaiparowits Plateau in order to put the microherpetofauna in their paleobiogeographical and paleoecological context.

Am Ende (1987) and Scott and Tschudy (in Peterson, 1969a) reported palynomorphs from the Dakota Formation. The presence of psilate and reticulate tricolporate suggested to her an age no older than Cenomanian. Am Ende (1987) noted the absence of Normapolles group pollens in the Dakota, and its absence in other western palynofloras of similar age, and suggests that the western United States was not in the Normapolles flora province. This observation is consistent with discussions of Cretaceous microflora provinces elsewhere (Srivastava, 1981; Herngreen and Chlonova, 1984).

A climatic interpretation of the Dakota Formation has been made based on a floristic approach (am Ende, 1987). The shortcomings of this approach, based on such an ancient pollen record, should be noted. Nonetheless, her interpretation of a warm temperate-to-subtropical environment seems reasonable.

Tschudy (in Peterson, 1969a) identified palynomorphs from the John Henry Member of the Straight Cliffs Formation. He makes the following paleoecological inferences based on those polynomorphs: 1) the lack of marine palynomorphs suggests isolation from the sea, including even occasional marine inundations; 2) the paucity of bisaccate conifer pollens indicates a marked distance from highlands; 3) the lack of *Azolla* indicates lack of permanent ponds and lakes, and deposition under palatal rather than lacustrine conditions; and 4) the presence of *Araucariacites*, *Gleichenioidites*, *Cicatricosisporites*, and *Vitreisporites* suggest a

subtropical climate. In short, the John Henry Member represents deposition in wet or swampy subtropical lowlands at some distance from highlands and marine waters.

Palynomorphs have also been reported from the Kaiparowits Formation of the Kaiparowits Plateau. Lohrengel (1969a, b) suggested that these palynomorphs indicated an "Upper Lancian" age. Eaton (1987a) argues that the only distinctive Maastrichtian taxon in Lohrengel's study (1969a, b) is *Azolla cretacea*.

Tschudy (in Bowers, 1972) and Eaton (1987a) make a far better case for a Campanian Age for the Kaiparowits Formation. Three taxa reported by Tschudy, *Araucariacites*, *Kuylisporites*, and *Rugubivesiculites*, are restricted to the Campanian.

The distinctive, enigmatic *Aquilapollenites* was reported by both Lohrengel (1969a, b) and Tschudy (in Bowers, 1972). This places the Kaiparowits Formation firmly in the *Aquilapollenites* microflora province as, presumably, was the entire western North America at this time (Srivastava, 1981; Herngreen and Chlonova, 1984). Subprovinces have also been proposed for the Maastrichtian of Western North America (Nichols, 1984; Tschudy and Tschudy, 1986). The southern microfloral province, south of paleolatitude 45°, is characterized by *Thomsonipollis magnificus*, and shares with the northern Rockies of the United States the genera *Arecipites* and *Pandaniidites* (Nichols, 1984). None of these taxa are present in the Kaiparowits Formation, possibly due to its earlier than Maastrichtian age.

Plant macrofossils have been recovered from the Wahweap Formation and include *Chara*, *Mesochara*, *Cercidiphyllum*? and an undetermined coniferous wood (Scott, in Peterson, 1969a). Little can be said of this flora except that water had to have been present to support the charophytes. Plant macrofossils have also been recovered in the Kaiparowits Formation (Gregory, 1951; Decourtin, 1978). Climatic inference by either floristic or morphological means was made by the authors of both the micro- or macrofloral studies. Noting the



uncertainties of floral-based inferences of climate, I venture the interpretation that the flora suggests warm, temperate-to-tropical conditions.

Invertebrates have also been reported from the Dakota, Straight Cliffs, Wahweap, and Kaiparowits Formations. The Dakota Formation invertebrates from the Kaiparowits Plateau have been reported by am Ende (1987). Most are near-shore marine to brackish water forms, although some (such as the *Corbiculidae*) are fresh to brackish water (am Ende, 1987). While useful for age assignment and correlation, these forms reveal little about the terrestrial ecosystem. These fossils further confirm the Cenomanian age suggested for the Dakota Formation (am Ende, 1987).

The invertebrates from the Straight Cliffs Formation of the Kaiparowits Plateau (Gregory, 1951) are somewhat less informative. These fossils, collected from more than one locality and probably from what would today be recognized as more than one member, represent both freshwater (*Viviparus*, *Planorbis*) and marine forms (*Ostrea*, *Cerithium*). Little can be concluded except that there were environmental changes during the deposition of the Straight Cliffs Formation.

The Wahweap Formation invertebrate fauna has been reported by Cobban (in Peterson, 1969a.) All taxa are typical freshwater forms.

The invertebrate fauna of the Kaiparowits Formation was initially reported by White (1876) and has subsequently been extensively studied (Reeside in Gregory and Moore, 1931; Yen, 1945; Reeside in Gregory, 1951; Decourten, 1978). Table 2 lists those invertebrates, with the nomenclature changed to reflect modern systematic practices. Specifically,

Tultoma thompsoni has been placed in *Viviparus*, following Hartman (1984); *Campeloma amarillensis* and *Goniobasis subortusa* have been placed in *Cleopatra* (Taylor, 1975); *Physa reesidei* has been placed in *Mesolantes* (Yen, 1954); and *Unio danae*, *U. haydeni*, and *U. brachyopisthaus* have been placed in *Plesielliptia* (Hartman, 1984). The reference of material to *Unio neomexicanus* presents special problems. Stanton (1916)

Table 2. Invertebrates reported from the Kaiparowits Formation. Sources: A) Reeside in Gregory and Moore, 1931; B) Yen, 1945; C) Reeside in Gregory, 1951; D) Decourten, 1978.

Phylum Mollusca		
Class Gastropoda		
Subclass Prasabranchia		
Order Mesogastropoda		
Family Viviporidae		
<i>Viviparus pangulichenis</i>	A, C	
<i>Viviparus canradi</i>	A	
<i>Viviparus thompsoni</i>	D	
<i>Viviparus</i> cf. <i>V. leoi</i>		C
<i>Viviparus</i> cf. <i>V. laevis</i>	A, C	
<i>Viviparus</i> or <i>Campeloma</i> sp.	A	
<i>Campeloma</i> sp.	A, C	
Family Ampullorididae		
<i>Mesolantes cretaceus</i>	B	
<i>Mesolantes</i> cf. <i>Physa reesidei</i>	A, C	
Family Pleuroceridae		
<i>Cleopatra subartusa</i>		A, C
<i>Cleopatra amarillensis</i>	D	
<i>Goniobasis</i> sp.	A	
Family Valvatidae		
<i>Volva?</i> sp.	D	
Subclass Pulmonata		
Order Planorbidae		
Family Planorbidae		
<i>Planorbis?</i> n.sp.	C	
<i>Bulinus subelongatus</i>	C	
Family Physidae		
<i>Physa</i> cf. <i>P. pleromatis</i>	C	
Order Stylomatophora		
Family Helicidae		
<i>Helix</i> sp.	C	
Class Pelecypoda		
Order Schizodontia		
Family Unionidae		
? <i>Unio</i> cf. <i>U. neomexicanus</i>		A
<i>Unio</i> aff. <i>U. amarillensis</i>	C	
<i>Plesielliptia</i> cf. <i>U. donce</i>	A	
<i>Plesielliptia</i> cf. <i>U. haydeni</i>	C	
<i>Plesielliptia</i> "suggesting" <i>U. brachyopisthaus</i>		A, C



established two cotypes, with the larger representing *Unio*, and the smaller probably *Plesielliptio brachyopisthaus* (Taylor, 1975). It is also likely that fossils previously identified only to genus would be placed in different genera today. It may also be noted that all of the species of *Viviparus* listed here have been referred to *Bellamya* (Taylor, 1975). While this assignment has some merit, I share the reservations of Hartman (1984) and follow him in retaining them in *Viviparus*. With the exception of the terrestrial *Helix*, all of the forms reported here are freshwater forms. Many of the taxa known from the Kaiparowits Formation have also been reported from the Cretaceous Fruitland Formation of the San Juan Basin, specifically *Cleopatra amarillensis*, *Mesolantes reesidei*, *Unio mexicanus*, *Unio amarillensis*, and *Plesielliptio brachyopisthaus*. The existence of many shared taxa should not be surprising, as these localities are spatially and perhaps temporally adjacent to each other. This similarity probably also suggests shared ecological conditions. The invertebrates appear to represent a heretofore unappreciated component of distinctive southern biota.

The archosaurs (including Aves) are represented, but poorly studied, on the Kaiparowits Plateau. Lull (in Gregory and Moore, 1931) reported ornithischian dinosaurs from the Kaiparowits Formation. Subsequently, Gilmore (in Gregory, 1950, 1951) reported theropod, hadrosaurid, and nodosaurian dinosaurs. The lambeosaurine hadrosaur, *Parasaurolophus*, was described from the Kaiparowits Formation by Weishampel and Jensen (1979). This relatively rare hadrosaur is known from the late Campanian Oldman Formation in Alberta, Canada (Parks, 1922), the late Maastrichtian Naashobito Member of the Kirtland Formation in the San Juan Basin, New Mexico (Wiman, 1931), and the variously interpreted late Campanian (Lucas and Williamson, 1993) or late Maastrichtian (Lindsay et al., 1978; Lindsay et al., 1981; Butler and Lindsay, 1985) Fruitland Formation, also in the San Juan Basin (Ostrom, 1961, 1963). It is probable that *Parasaurolophus* was both more abundant and persisted later in the southern faunas.

The ornithomimid, *Ornithomimus velox*, has also been reported from the Kaiparowits Formation (Decourten, 1978; Decourten and Russell, 1985). This species was previously known only by the type specimen (Marsh, 1890) from the late Maastrichtian Denver Formation of Colorado (Soister, 1978). The occurrence of *O. velox* in the Kaiparowits Formation has been used as evidence of late Maastrichtian Age (Decourten and Russell, 1985), an assessment not followed here.

An unnamed species of the enaniornithine bird *Avisaurus* has recently been reported from the Kaiparowits Formation (Hutchison, 1993). This genus, initially thought to be a dinosaur, was originally described from the late Maastrichtian Hell Creek Formation of Montana (Brett-Surman and Paul, 1985). Crocodilians, not formally reported from the Kaiparowits Formation, are also present. Teeth, seen by the author, probably represent the genera *Leidyosuchus* and *Brachychampsa*.

In summary, the archosaur fauna of the Kaiparowits Formation remains an open field for research. The persistence of early forms, such as *Parasaurolophus* in southern faunas has been noted previously (Hunt and Lucas, 1993). If the inferred Campanian age for the Kaiparowits is correct, it suggests that many Maastrichtian species in northern faunas had an earlier occurrence in the south as well.

The mammalian fossils have been the best-studied element of the Cretaceous faunas on the Kaiparowits Plateau. Intensive prospecting and screen washing have produced a remarkable series of mammalian faunas from Cenomanian to Campanian age.

The Dakota Formation contains a moderately diverse assemblage from the middle Cenomanian. The most significant element of this fauna are the marsupials *Pariadens*, *Alphadon*, and *Protalphadon* (Cifelli and Eaton, 1987; Eaton, 1993). These taxa represent the earliest unequivocal marsupials known in the world. Due to the similarity between latest Cretaceous North and South American marsupial faunas, one immigration event has



been postulated (Stehli and Webb, 1985). The presence of two families of marsupials in the Cenomanian implies either an earlier migration than previously postulated or multiple migrations. The diversity of marsupials at this time suggests an origin of the order perhaps as early as Neocomian (Eaton, 1993).

Mammals have also been reported from the Smoky Hollow Member and John Henry Member of the Straight Cliffs Formation (Eaton and Cifelli, 1988; Cifelli, 1990c). These faunas document a diverse assemblage of therian mammals at an otherwise poorly known time interval. The taxa includes spalacotheriid symmetrodonts, metatherian-eutherian grade, and marsupials. Noteworthy is the absence of eutherians (Cifelli, 1990c).

The Wahweap Formation also contains a diverse mammalian fauna (Cifelli and Madsen, 1986; Eaton and Cifelli, 1988; Cifelli, 1990b, d). The nontribosphenic spalacotheres remain an abundant element of this fauna. While the large cimolomyid *Meniscoesues* occurs questionably and if so, rarely here, it is an abundant element in northern faunas. This agrees with observations from the San Juan Basin (Flynn, 1986) and the suggestion that this may be one of the few mammals that reflect the north-south dichotomy seen in dinosaurs (Sloan, 1969). *Paracimexomys* is common, but pediomyids and the stagodontids are absent. *Paracimexomys* is rare and pediomyids and stagodontids are abundant in northern faunas (Clemens et al., 1979). This has been suggested as a north-south differentiation (Eaton and Cifelli, 1988).

The evidence for an abundance of stagodontids in Aquilian and younger northern faunas is strong, and has been noted previously (Fox and Naylor, 1986); however, it is interesting to note their presence in the earlier Dakota and Straight Cliff faunas. The absence of pediomyids may reflect unfavorable local ecological conditions, as these mammals are present elsewhere in the Fruitland Formation of New Mexico (Clemens, 1973; Armstrong-Zeigler, 1978), the Aguja Formation of Texas (Rowe et al., 1992), and even in the "El Gallo Formation" of Baja California del Norte (Lillegraven, 1972); how-

ever, it has been suggested that they are rare in those faunas (Cifelli, 1990c). There are few species shared between the Wahweap and the similar age Milk River faunas. This suggests either ecological or chronological differences or both (Eaton and Cifelli, 1988). The Wahweap eutherians are among the earliest in North America. Their great morphological divergence and lack of plausible Asian ancestors suggest even greater North American antiquity than previously suspected (Cifelli, 1990d).

The Kaiparowits mammals are also well-documented (Eaton and Cifelli, 1988; Cifelli, 1990a, d). Pediomyids, stagodontids, and *Meniscoesues* are absent and *Paracimexomys* remains common. The spalacotheriid have by this time apparently disappeared. Few mammalian species are shared with northern faunas of equivalent age (Eaton and Cifelli, 1988; Cifelli, 1990a, d). In general, the Kaiparowits mammalian fauna reflects the loss of archaic taxa and the radiation of modern taxa, suggesting a distinctive southern fauna.

The Kaiparowits Plateau affords us a view of the southern Cretaceous biota through time. The original recognition and characterization of southern and northern biotas in the Cretaceous was made for the latest Maastrichtian (Lancian) based chiefly on dinosaurs (Sloan, 1969). With additional study, these biotas have held up well (Lehman, 1987; Lucas and Hunt, 1989), and subsequently more, less well-established biotas have been proposed for the east (Denton and Gallagher, 1989; Denton, 1990; Denton et al., 1991; Denton and O'Neill, 1993, 1995), the west coast (Morris, 1973, 1981, 1982), and the extreme north (Nelms, 1989; Clemens and Nelms, 1993).

In the Lancian, the southern biota is characterized by the sauropod *Alamosaurus*, presumably an immigrant from South America (Sloan, 1969; Lucas and Hunt, 1989). Unfortunately, the taxon is never abundant and has been thought of as having immigrated not much before Lancian time (Lucas and Hunt, 1989). Recent evidence does suggest that *Alamosaurus* may have appeared earlier in southern Arizona (McCord, 1997), but its absence in the



Kaiparowits and older formations could equally well be interpreted as the result of sediments that were too early an age, or to insufficient collecting.

In general, the Kaiparowits dinosaur fauna, as presently understood, consists of temporally and spatially wide-ranging taxa that tells us little about the development of the southern community through time. As for other pre-Lancian southern dinosaur faunas, the only valid generality may be that they contain only chasmosaurine ceratopsians (Lehman, 1996), thereby excluding the ubiquitous *Triceratops* and its kin.

The mammalian faunas reflect, I feel, increasing provincialism through time. In the early Dakota and Straight Cliffs faunas, stagodontids are present (Cifelli and Eaton, 1987; Eaton and Cifelli, 1988; Cifelli, 1990c; Eaton, 1993), although they are generally thought to characterize the northern biotas (Sloan, 1969; Cifelli, 1990c), but the pelyomyids, rare or absent in the southern faunas, are not present (Cifelli, 1990c). In the Wahweap Formation, pelyomyids and stagodontids are absent, *Paracimexomys* is present, and there are few species shared with northern faunas (Eaton and Cifelli, 1988; Cifelli, 1990b), suggesting developing provincialism. Nevertheless, *Meniscoes*, a "northern form" (Eaton and Cifelli, 1988) is still present. By Kaiparowits time, *Paracimexomy* is present and pelyomyids, stagodontids, and *Meniscoes* are absent (Eaton and Cifelli, 1988; Cifelli, 1990a), and there are few taxa shared with northern faunas, suggesting full development of provincialism.

Unfortunately, the microfloras and macrofloras from the Kaiparowits Plateau do little to reinforce any but the broadest generalities about developing provinciality in the Late Cretaceous. The Dakota palynoflora (am Ende, 1987) merely confirms that although by the Cenomanian a Normapolles-group pollen may have spread throughout the east, it was not present west of the epicontinental sea (Srivastava, 1981; Henggreen and Chlonova, 1984). Similarly, the Kaiparowits palynoflora (Lohrengel, 1969a, 1969b; Tschudy, in Bowers,

1972) confirms only that by the Campanian, the west is characterized by *Aquilapollenites* pollen (Srivastava, 1981; Henggreen and Chlonova, 1984), but the distinctive elements of the southern Rockies subprovince (Nichols, 1984; Tschudy and Tschudy, 1986), whose limits approximate that of the *Alamosaurus* community (Sloan, 1969), are not present. Explanations for the absence of typical southern Rockies subprovince forms include that collecting was inadequate; local environmental conditions were unfavorable; that the paly-nomorphs, which supposedly characterize the southern Rockies, don't characterize it; or that this subprovince does not yet exist as a unique floral assemblage prior to the Maastrichtian.

Wolfe and Upchurch (1987) also suggest the presence of a distinctive plant biota, roughly corresponding to the *Alamosaurus* community, in the Late Cretaceous. Leaf physiognomy and wood structure analysis suggests a megathermal (warm month mean <20 °C), open canopy, broad-leaved, evergreen woodland. Unfortunately, the floristic analysis used (Gregory, 1951; Decourten, 1978) does nothing to confirm or deny this.

The small reptiles and amphibians do not show much differentiation between the southern and northern biotas (Sloan, 1969). Perhaps even more telling, the topic of northern and southern provincial faunas is generally ignored in studies of late Cretaceous microherpetofaunas.

The one element of these microherpetofaunas that does appear to represent a southern group is the polyglyphanodontines. Polyglyphanodontines, in the restricted sense, are currently known from the Maastrichtian North Horn Formation of Utah, as well as the Campanian "El Gallo Formation" in Baja California del Norte (Estes, 1983), the Turonian Smoky Hollow Member of the Straight Cliffs Formation, and the Campanian Kaiparowits Formation of the Kaiparowits Plateau (this paper). This subfamily is not known to the north, nor, curiously, in the Fruitland and Kirtland Formations of the San Juan Basin, New Mexico (Armstrong-Ziegler, 1978, 1980; Sullivan, 1981) or the Aguja



Formation of Texas (Miller, pers. comm.). The absence of polyglyphanodontines from these southeastern faunas is perplexing. It is tempting to ascribe their absence from the Aguja Formation to floristic differences. Palynomorphs from the Aguja suggest that it belonged to the eastern Normapolles microfloral province rather than to the typical *Aquilapollenites* flora typical for the late Cretaceous of the western interior (Baghai, 1994). Such a difference may imply absence of a preferred food source for the likely herbivorous lizards or climatic differences.

Such an explanation cannot be invoked for the San Juan Basin, however, which appears to belong to the more typical *Aquilapollenites* microflora (Tschudy, 1973). The occurrence of *Paraglyphanodon* in the Turonian of the Kaiparowits Plateau represents the earliest find of polyglyphanodontine in North America. Recent phylogenetic analysis (Denton and O'Neill, 1995) suggests that the polyglyphanodontines, as presently constituted, may represent a paraphyletic grade of teiid lizards, but a Polyglyphanodontidae, sensu stricto including *Polyglyphanodon*, and likely *Paraglyphanodon* and the new taxon here, as well as the Asian *Cherminisaurus*, probably does exist. One genus, *Peneteius*, generally referred to the Teiinae (Estes, 1969, 1983), has been reported from northern faunas. It is unclear if this form belongs to the polyglyphanodontine grade, clade, or to another subfamily altogether.

The early occurrence of *Paraglyphanodon* suggests a North American origin for this subfamily. It seems likely that polyglyphanodontine distribution must have extended continuously to the north and ultimately to Asia, to account for their later distribution. Either *Peneteius* is a polyglyphanodontine, or the Turonian occurrence here suggests that the polyglyphanodontines were able to disperse to the north (or possibly from Asia) before the well-studied Judithian and Lancian faunas of the north.

In summary, in Judithian and Lancian times, the polyglyphanodontines are known with certainty only from the western localities of the southern community and Asia. The

Turonian occurrence of a polyglyphanodontine on the Kaiparowits Plateau suggests sufficient time for an as yet undiscovered distribution of polyglyphanodontines through western North America to Asia.

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Potential for Paleoecological Study of Mesozoic Marine Fossils in the GSENM

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ABSTRACT

■ The Mesozoic was a time of significant oceanographic, environmental, biological, and ecological changes and marked the development of modern conditions. These rapid faunal diversifications and shifts in ecological structure have been referred to as the "Mesozoic Marine Revolution." Several marine incursions are represented within the extensive Mesozoic deposits in the Grand Staircase-Escalante National Monument. However, very little is known about the paleoecological dynamics of the marine faunas within this region, thus creating a gap in our understanding of global patterns of paleoecological change during this critical time interval.

Fossil evidence can be used in a number of ways including age correlation and the reconstruction of ancient environments. Paleontological information can also be used to document and understand evolutionary and ecological trends through time. Results from paleoecological analyses can provide insights into the responses of ecosystems and communities to global change processes (Jablonski and Sepkoski, 1996). However, little paleoecological study has been conducted on marine fossil assemblages in the Grand Staircase-Escalante National Monument (GSENM). Thus, in this aspect, the paleontological resources in the GSENM have been underutilized in the past, but may yield significant scientific information with detailed paleoecological analyses in the future.

Most of the fossils within the GSENM are Mesozoic in age (Gillette and Hayden, 1997), and because this interval was marked by significant global change, paleoecological analysis of the GSENM paleontological resources could provide important scientific data about the response of organisms to environmental perturbations. The Mesozoic is a critical

Detailed paleoecological analyses of marine faunas within the GSENM would provide information on: 1) evolutionary trends within this biogeographic region, 2) paleoecological changes related to the Mesozoic Marine Revolution, 3) characteristics of low-diversity, nearshore marine assemblages, 4) responses of assemblages to major environmental perturbations due to sea level changes, and 5) the unique paleoenvironmental and ecological conditions which existed in this region.

transitional period in the development of modern oceanographic, geographic, climatic, biological, and ecological conditions. As the Atlantic Ocean opened up, the supercontinent of Pangaea began to break apart, and continents started drifting to their current configurations. This permanently altered ocean circulation patterns, which, in turn, resulted in changing wind and precipitation patterns (Parrish, 1992).

Along with these environmental changes, the Mesozoic was a time of significant biological and ecological changes as well. There was a rapid increase of marine faunal diversity through the Mesozoic with the origination of many taxa significant in today's oceans (Sepkoski, 1981). Because the Mesozoic was the time when the "Paleozoic Fauna" became replaced by the "Modern Fauna" (Sepkoski, 1981), it can be considered as a transitional



period to the type of marine fauna present today. Accompanying this very rapid taxonomic diversification, there were also significant changes in the ecological structure of marine communities. For example, the number of active infaunal organisms and the depth to which they were burrowing increased substantially during the Mesozoic (Sepkoski et al., 1991; Thayer, 1979) as did the number of skeletonized and boring organisms on hard-ground habitats (Palmer, 1982). These changes, among many others, have been attributed to increasing predatory pressure that arose during the Mesozoic due to the rise of increasingly effective predators—in effect an “arms race” between predators and prey (Vermeij, 1977). These ecological changes are so great that this interval has been termed the “Mesozoic Marine Revolution” (Vermeij, 1977).

The global environmental, biological, and ecological changes that occurred during the Mesozoic provide a backdrop for examining long-term evolutionary patterns in the GSENM fossil record. Superimposed upon these long-term processes are regional environmental perturbations that occurred in this region. For example, throughout the Mesozoic, this area was often at the edge of the marine depositional system, and even relatively minor sea level changes could result in large environmental shifts, which are reflected in the repetitive marine, marginal-marine, and nonmarine beds within the Monument and surrounding areas (Blakey et al., 1996; Doelling and Davis, 1989; Peterson, 1994). The combination of short-term and long-term environmental changes provides an opportunity to study the ecological dynamics of organisms, communities, and ecosystems in response to fluctuating conditions.

Case Study from the Mid-Jurassic Carmel Formation of South-Central Utah

Although the Late Cretaceous fauna is probably the best documented marine invertebrate

fauna within the GSENM (Dyman et al., 1998), one example of the type of paleoecological information that could potentially be obtained from the GSENM fossil resources comes from the Middle Jurassic Carmel Formation in south-central Utah. The Carmel Formation was formally described by Gregory and Moore (1931). The formation contains marine and marginal-marine deposits, which were formed within or adjacent to the southern end of an epicontinental seaway that covered the U.S. Western Interior during Bajocian and Bathonian times (Imlay, 1980). Although most of the studied fossil material from the Carmel Formation has been from outside the GSENM boundaries (Imlay, 1964; Sohl, 1965; Wilson and Palmer, 1994; Tang 1996; Tang and Bottjer, 1997; Wilson, 1997), there are Carmel Formation marine invertebrates present within the Monument (Imlay, 1964; Sohl, 1965; Gillette and Hayden, 1997).

Much of the formation within the GSENM is gypsiferous and clearly not fully marine (Doelling and Davis, 1989). However, the faunal evidence—including the presence of corals, crinoids, and echinoids (Imlay, 1964; Gillette and Hayden, 1997)—suggests that normal marine conditions existed in some intervals. In other areas of the Carmel Formation, there are both marginal-marine (Wilson and Palmer, 1994) and marine assemblages present (e.g., Tang et al., 1994; Tang, 1996; Tang and Bottjer, 1997). Paleoecological research in the Carmel Formation conducted by Tang (1996) included study at different scales: 1) within a single assemblage; 2) between assemblages at one locality; 3) comparison with Carmel Formation assemblages with those from other Jurassic strata worldwide, and 4) long-term regional patterns including data from other Jurassic formations in the U.S. The results of previous studies have provided information about the lateral distribution of fossils within depositional facies, the biogeographic affinities of some taxa, the paleocommunity structure of specific assemblages, and the life habitat of organisms. In the following discussion, the unique aspects of the Carmel Formation fauna will be highlighted in order to underscore the



potential rewards from paleoecological study of invertebrate assemblages within the GSENM.

At the smallest scale, the analysis of single samples can provide information about the structure of communities and the paleobiology of their constituent taxa. For example, one study of a crinoidal limestone occurrence at Mount Carmel Junction resulted in its identification as one of the youngest shallow-water examples in the fossil record (Tang et al., 1994, in prep). The thick accumulation of partially articulated stalked crinoid is somewhat anachronistic in that most crinoidal limestones are found within the Paleozoic (Ausich, 1997). During the Mesozoic, stalked crinoids begin a retreat into the deep sea (Bottjer and Jablonski, 1988), possibly as a result of the increasing predation pressures, which are part of the Marine Mesozoic Revolution (Meyer and Macurda, 1983). If predation is a major control on the distribution of Mesozoic shallow-water stalked crinoids as Meyer and Macurda (1983) have predicted, then this anomalous occurrence of a crinoidal limestone in the Carmel Formation suggests that there may be unique environmental and ecological factors at work in this region of the epicontinental seaway that could potentially be worth studying inside the Monument in the future.

As a whole, the fauna of the Carmel Formation—and of the Middle and Upper Jurassic strata of the U.S. Western Interior—is fairly low-diversity as compared to other parts of the world (Tang, 1996; Tang and Bottjer, 1996). There is low within-community diversity (alpha), between-community diversity (beta diversity), and regional diversity (gamma) (Tang, 1996). The low faunal diversity appears to be characteristic of trace fossils, soft-bottom fauna, and hard-substrate fauna (Tang, 1996). A number of potential explanations have been forwarded to account for low diversities within the Jurassic Western Interior epicontinental seaway—such as restricted access, harsh environmental conditions, fluctuating environmental conditions (Tang, 1996), and nonmarine influences (Wilson and Palmer, 1994)—but more research is needed before conclusive evidence can be found.

The marine invertebrate faunas of the Jurassic Western Interior were the focus of an evolutionary paleoecological analysis of patterns of stability in the fossil record. By comparing marine invertebrate species, genera, and paleocommunities through the 20 million-year span of the Jurassic U.S. epicontinental seaway, Tang and Bottjer (1996) documented long intervals of faunal stasis. This result was unexpected because the Jurassic was an interval of great global changes, as discussed above, and because the pattern did not resemble one of "coordinated stasis" as documented by other workers. Coordinated stasis is a pattern in the fossil record where taxa and their paleocommunities stay stable for millions of years before undergoing near-synchronous, rapid turnover (Brett and Baird, 1995). While Tang and Bottjer (1996) documented general stability—the same taxa and assemblages would reappear even after major sea level changes and environmental shifts—they found that there did not appear to be intervals where large portions of the fauna went extinct at the same time. Thus, individual taxa, and the paleocommunities which included these taxa, could be stable, but did not seem to respond in a coordinated way with others.

It was hypothesized that many potential factors may be responsible for this pattern of relative long-term stability (Tang and Bottjer, 1996):

- 1) Due to the shallow nature of the epicontinental seaway and the presence of many topographic highs, it is possible that the organisms employed "faunal tracking," where populations were able to migrate along with their preferred, optimal environment as sea levels rose and fell. Thus, as the regional environment experienced many changes, the local conditions where the organisms lived stayed relatively stable.
- 2) The dominant organisms in the Jurassic strata are bivalves (Imlay, 1980; Tang, 1996; Tang and Bottjer, 1996), which possess fairly long species durations (Stanley, 1979).
- 3) Based on a number of lines of evidence, the fauna in the Jurassic Western Interior appear



to be eurytopic in nature (generalists), and have been hypothesized to have longer species durations (Eldredge and Cracraft, 1980).

Data from Brett (pers. comm) and Tang and Bottjer (1996) suggest that assemblages that exhibit the most amount of stability in the face of environmental perturbations are those which are low-diversity and in nearshore, shallow-water environments. This provides evidence that high-frequency disturbances and low-diversity ecological structure may confer stability upon an ecosystem—an idea which has been debated for decades in the ecological literature. Further paleontological work in the Mesozoic of the U.S. Western Interior—including within the GSENM—as well as in other parts of the geological column could provide more information about the stability and instability of low-diversity, shallow-water assemblages in the face of global and regional environmental changes.

Paleoecological Research Requirements in the Grand Staircase-Escalante National Monument

In order to conduct meaningful and statistically significant paleoecological analyses, large numbers of fossil individuals must be collected to recover a representative population and assemblage. There are many rigorous methods for determining the number of individuals needed for statistical analyses—most require preliminary sample analysis and subsequent resampling (for review, see Krebs, 1989). Clearly, different situations will require different sample sizes and different volumes of fossiliferous rock to be collected. For example, in high-diversity assemblages, extremely large volumes of material must be collected in order to obtain a representative collection of species (CoBabe and Allmon, 1994). For the low-diversity, fossil-rich Jurassic invertebrate

assemblages examined by Tang (1996), between 8,000 and 16,000 cubic centimeters of bulk fossil samples were collected, yielding between a few hundred to a few thousand identifiable skeletal parts. The collection of large sample sizes does not pose as large an issue for invertebrate fossils as it may with vertebrate material.

Another aspect of conducting quantitative paleoecological analyses is the collection of replicate samples and the assessment of lateral variability. Statistical analyses often require assessment of internal variability, and the collection of replicate samples is fundamental to this kind of analysis. For example, assemblages cannot be deemed different until the underlying variability in natural communities is understood (e.g., Bennington and Bambach, 1996). Because the distribution of fossils can result from a number of factors—including natural patchiness, transport by water and sediment movement, and burrowing activity by organisms—it is important to quantitatively assess the variability by collecting a number of samples at one place and at randomly spaced intervals. These type of studies are becoming recognized as important components of paleoecological analyses (CoBabe and Allmon, 1994; Bennington and Bambach, 1996).

Along with bulk fossil samples, hand samples representative of the strata surrounding the fossil-bearing beds are needed in order to reconstruct the environmental and stratigraphic context of the fossil assemblages. Thin section analyses may also yield the presence of organisms not previously identified from bulk fossil samples.

Thus, in order for significant, rigorous paleoecological work to be conducted within the GSENM, scientists must be allowed to collect fairly large numbers of individual fossil specimens and rock samples from surrounding strata. These bulk fossil samples may or may not involve large volumes of excavated rock depending on the size and density of fossils. However, the need for replicate samples and lateral comparisons must also be recognized.



In order to collect and retrieve fairly large numbers of bulk fossil samples, paleoecologists may need to access outcrops with four-wheel drive vehicles, not just on foot. In addition, since pilot studies may first be needed in order to estimate the correct sample sizes needed for statistical analyses, it is possible that scientists may need to revisit a locality in order to collect more bulk fossil samples.

Potential Paleoecological Research within the GSENM

Since virtually nothing is known about the paleoecology or paleocommunity dynamics of the marine invertebrate assemblages in the GSENM during the critical time interval of the Mesozoic, future paleoecological research within the Monument may provide many insights into the biogeography, evolution, and structure of the fauna. It is clear that there are many invertebrate fossil resources within the boundaries of the Monument (Gillette and Hayden, 1997; Dyman et al., 1997). Many of these taxa have already been identified and the general stratigraphic and sedimentological context has already been well-defined (Peterson, 1994; Doelling and Davis, 1989). Thus, the background needed for detailed paleoecological analyses has already been established and further paleontological research could readily provide new insights.

Due to the unique paleoenvironmental conditions that existed in this part of North America during Mesozoic times, paleoecological study of the marine invertebrate assemblages within the GSENM may be used to understand the dynamics of marginal marine ecosystems, low-diversity communities, and biogeographically isolated faunas. Its location at the edge of the Mesozoic epicontinental seaway means that this general area was sensitive to even minor changes in sea level, and environmental conditions shifted often during

the Mesozoic. These sea level changes are seen in sedimentological, stratigraphic, and preliminary paleontological data. However, further paleoecological study will allow scientists to examine how paleocommunities and the interactions between organisms may have changed in response to fluctuating sea levels and environments.

In addition, because the Mesozoic is such a critical transition period for marine fauna (i.e., the Mesozoic Marine Revolution), the study of these assemblages could be placed in a global context in order to understand the processes of biological radiation, resilience of communities in the face of environmental perturbations, and the effect of global change on the organization of biological systems.

Acknowledgments

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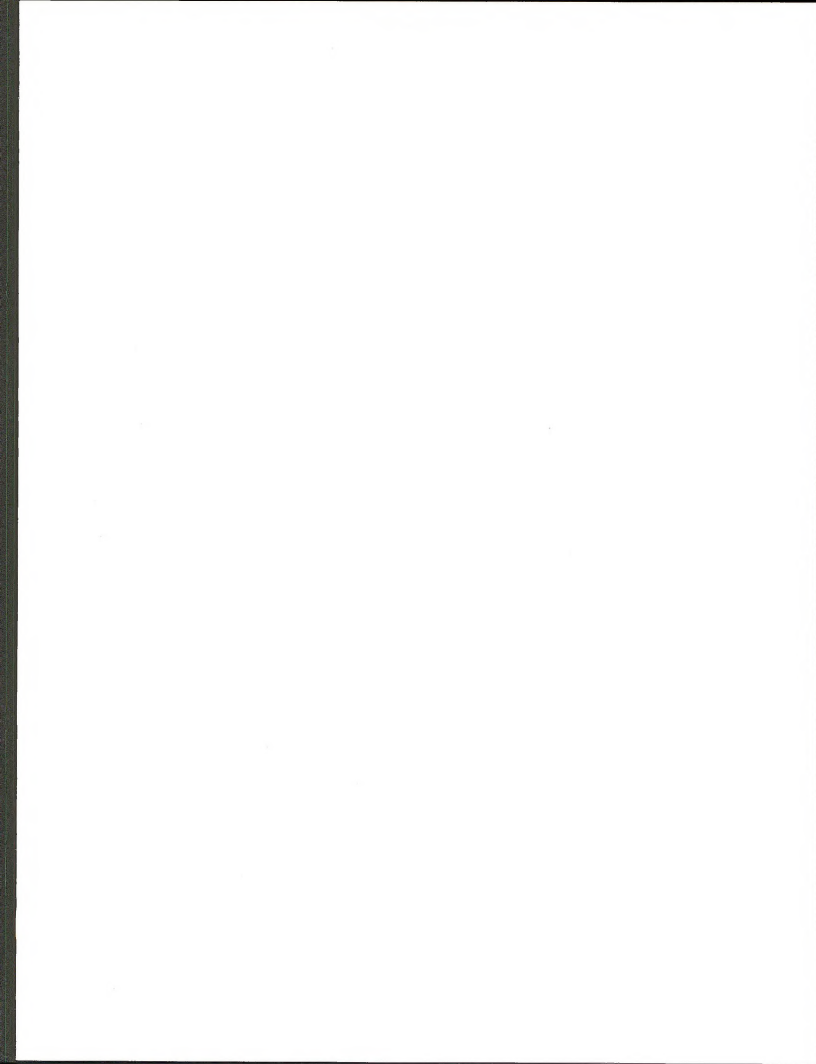


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GENERAL SECTION







Quaternary Resources: Interdisciplinary Research in the Grand Staircase-Escalante National Monument

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If I were to retile this presentation, I would reverse a geological axiom "the present is the key to the past" to "the past is the key to the present." This reversal of a concept is especially pertinent to the Colorado Plateau, those Federal lands on the Colorado Plateau, and the potential as a management guide for the newly created Grand Staircase-Escalante National Monument (GSENM).

For nearly two decades my colleagues, our students, and myself have conducted multidisciplinary research on the deposits and resources of the Quaternary period (the past 2 million years) on Federal, State, and private lands on the Colorado Plateau. Much of the results of our research remains in in-house documents of the National Park Service (NPS) and other agencies; however, considerable information has been public in professional meetings, professional papers, (Davis et al., 1984; Mead et al., 1984, 1986a, 1987, 1991; Mead and Agenbroad, 1989, 1992; Agenbroad

ABSTRACT

■ As recently as 1982, many resource managers were unaware of the potential for Quaternary resources, or the nature of such resources, on Federal lands on the Colorado Plateau. The discovery of mammoth boli in Bechan Cave, Utah, initiated a new awareness of Quaternary resources and the interdisciplinary nature of research of these resources. Contracts with the U.S. Department of the Interior, Rocky Mountain Region, and the Western Region of the National Park Service led to investigations within the Plateau National Parks. These investigations produced geological, paleontological, ecological, paleoenvironmental/paleoclimatic, and archaeologic results. Integration of these data sets has generated new models of the prehistory of the Colorado Plateau. The Grand Staircase-Escalante National Monument contains an outstanding potential to complement and add to prior research, as well as open new research projects and areas of study. An analysis of selected categories of existing data sets serves as a predictive model for resources to be discovered in the Monument. The resulting model provides a basis for resource management and protection.

and Mead, 1989) and publications for the lay-public (Nelson, 1990; Agenbroad, 1990). Some of our results have even been incorporated into NPS-sponsored books such as *The Ice Age History of Southwestern National Parks* (Elias, 1997). Our research methodology is outlined in Table 1.

The "Plateau Prehistory Myth"

Quaternary research on the Colorado Plateau has been hampered (pre-1980) by a two-pronged myth initially proposed by archaeologists for the Great Basin, transferred to the

Table 1. Paleoenvironmental features and data sources used to construct a geochronologic and paleoecological framework (from Agenbrood and Mead, 1992; Agenbrood et al., 1990, 1993).







Temporal Interval	Paleontologic	Archaeologic	Geologic	Hydrologic
Pre-11,000 B.P. (9,000 B.C.)	Extinct fauna: mammoth, horse, camel, shrub oxen, sloths, mountain goat	Paleo-Indians Clovis projectile point  Folsom projectile point 	Cut and fill (erosion) Color and texture of sediment Guide fossils (vertebrate and invertebrate) Soils Sand dunes	Cut and fill (erosion/deposition) Oxidizing/reducing environment Water table position Lacustrine/paludal deposits Invertebrates and amphibians
11,000 B.P. (9,000 B.C.) to 7,000 B.P. (5,000 B.C.)	Absence of extinct fauna (modern fauna present)	Paleo-Indians: Plano cultures  Early Archaic cultures 	Cut and fill (erosion) Color and texture of sediment Guide fossils (vertebrate and invertebrate) Soils Sand dunes	Cut and fill (erosion/deposition) Oxidizing/reducing environment Water table position Lacustrine/paludal deposits Invertebrates and amphibians
7,000 B.P. (5,000 B.C.) to 2,000 B.P. (0 B.C.)	Absence of extinct fauna (modern fauna present) Domestic ? forms	Absence of Plano Middle and late Archaic cultures 	Cut and fill (erosion) Color and texture of sediment Guide fossils (vertebrate and invertebrate) Soils Sand dunes	Cut and fill (erosion/deposition) Oxidizing/reducing environment Water table position Lacustrine/paludal deposits Invertebrates and amphibians
2,000 B.P. (0 B.C.) to 0 B.P. (1950 A.D.)	Absence of extinct fauna (Modern fauna present) Domestic ? forms	Ceramics, Basketmaker and Pueblo artifacts 	Cut and fill (erosion) Color and texture of sediment Guide fossils (vertebrate and invertebrate) Soils Sand dunes	Cut and fill (erosion/deposition) Oxidizing/reducing environment Water table position Lacustrine/paludal deposits Invertebrates and amphibians





Table 1 (Continued).

Chronologic	Palynologic	Macrobotanical	Malacofauna	Environmental and Paleoclimatic Interpretations
Buried organic remains Charcoal as sediment Buried cultural features (hearths) Fossils Packrat midden chronology	Chronologically controlled Pollen profiles	Plant remains Dung Packrat middens	Boreal-mesic species	Interpret fossil vs. modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the temporal interval
Buried organic remains Charcoal as sediment Buried cultural features (hearths) Fossils Packrat midden chronology	Chronologically controlled Pollen profiles	Plant remains Dung Packrat middens	Fewer number of boreal species; ponding phases	Interpret fossil vs. modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the temporal interval plus new cultural adaptations
Buried organic remains Charcoal as sediment Buried cultural features (hearths) Fossils Packrat midden chronology Ceramics for relative dating	Chronologically controlled Pollen profiles	Plant remains Dung Packrat middens	Spotty records of mesic species indicating local ponding phases	Interpret fossil vs. modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the Temporal interval plus new cultural adaptations Presence or abandonment of areas previously occupied
Buried organic remains Charcoal as sediment Buried cultural features (hearths) Fossils Packrat midden chronology Ceramics for relative dating	Chronologically controlled Pollen profiles Evidence of cultigens	Plant remains Dung Packrat middens Evidence of cultigens	Spotty records of mesic species indicating local ponding phases	Interpret fossil vs. modern communities of plants and animals Infer temperature and moisture condition Describe geologic processes at work in the temporal interval plus new cultural adaptations Presence or abandonment of areas previously occupied



Colorado Plateau, and ingrained in the literature until it has risen to the status of "fact." That myth, in its general form, is stated something like this: "There were no Paleo-Indians on the Colorado Plateau due to a paucity of Pleistocene large animals necessary for their existence." That statement has: 1) hindered research into the presence, abundance, or absence of Pleistocene large animals (megafauna) on the Colorado Plateau, and 2) focused the archaeological research on the overabundant Anasazi remains on the Colorado Plateau—ignoring 9,000 years of Plateau prehistory that predate Anasazi (ceramic) cultures.

My intent, in this presentation, is to destroy that myth! It is groundless and has, in fact, hindered Pleistocene and Holocene research and has had a resultant effect on resource recognition and management.

I wish to address the two major points of what I will term the "Plateau Prehistory Myth." That is, I wish to address the presence of Pleistocene megafauna and the concurrent presence of pre-2000 year B.P. human cultural groups. Then I would like to make some general comments on the geoclimatic changes in the past 11,000-12,000 years. I will conclude with some management suggestions and recommendations pertinent to the GSENM.

Plateau Pleistocene Megafauna

The following figures supply dot-map distributions of documented localities for most of the large animals (megafauna) of the Colorado Plateau.

Mammoths

Figure 1 depicts the known locations of mammoth remains on the Colorado Plateau. There are a

total of 41 mammoth localities, of which 13 have yielded radiocarbon dates. The four youngest dates yield a weighted average of $11,270 \pm 65$ years B.P. (Agenbrood and Mead, 1989). Intuition would suggest mammoth remains would tend to cluster near major drainages and this is reflected in the dot map. Of particular interest to the research and management of GSENM is the cluster of mammoth localities adjacent to the southern and eastern portions of the Monument. There is a relatively high potential for mammoth remains or trace fossils (Hansen, 1980; Davis et al., 1984; Mead et al., 1986b), or rock art within the Monument.

Bison

Figure 2 is a dot map of documented bison distribution on the Colorado Plateau. A note of caution must be inserted here—it is my feeling that the bison distribution suffers from a bias. That bias is in the form of passing-by bison remains because they are mistakenly identified as the remains of domestic cattle. The heaviest concentration of documented

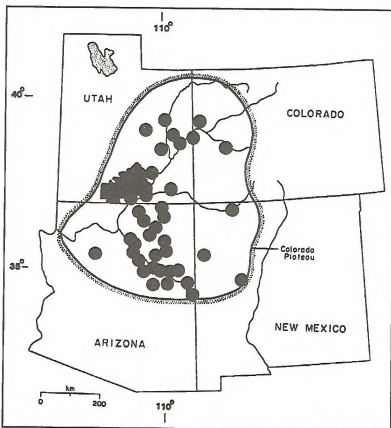


Figure 1. Documented mammoth localities on the Colorado Plateau.

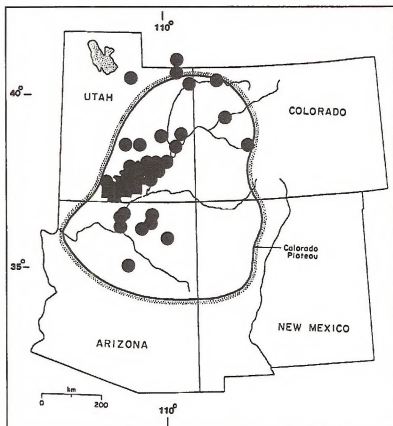


Figure 2. Documented bison localities on the Colorado Plateau.

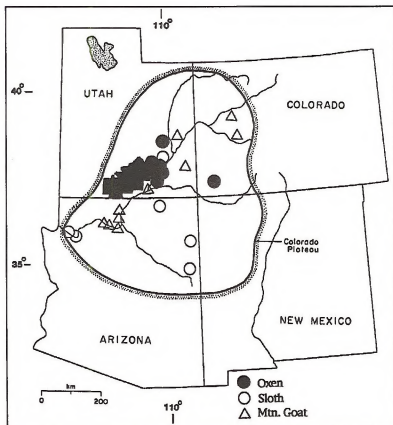


Figure 3. Documented oxen, sloth, and mountain goat localities on the Colorado Plateau.

bison remains and trace fossils (Hansen, 1980; Mead and Agenbroad, 1992) is in the western reaches of the Colorado and Green River drainages. The heavy concentration on the north and northeastern boundaries of the Monument provides a high level of predictability for bison remains, trace fossils, and rock art within the GSENM.

Oxen, Sloths, and Mountain Goats

Figure 3 depicts the distribution of these large grazers/browseers. These animals are known from osteological remains, as well as trace fossils (Martin and Wright, 1967; Martin and Hansen, 1973; Long et al., 1974; Agenbroad and Mead, 1987). The concentration of shrub ox and sloth remains northeast and east of the GSENM provides a high predictability that such remains will also be present in the Monument.

Tapirs, Camels, and Horses

Another group of grazers/browseers is represented in Figure 4. Of this group, camels and horses have the most proximal relationship to the GSENM. It is suggestive that remains of this group may also be found within the Monument. Horse distribution, similar to bison distribution, may reflect bias, such as concluding fossil horse remains are domestic animals.

Mammoth and Bison Rock Art

Proxy data for mammoths and bison exists in the form of rock art, pictographs, and petroglyphs.



The distribution of rock art for mammoths (Figure 5) is more restricted than the remains of the animal. Bison rock art is nearly as widespread as remains of the animals. In both cases, rock art is proximal to the GSENM and predicts similar discoveries will be made within the Monument. Rock art—especially bison—is sometimes accompanied by horses and riders. There is no doubt that bison rock art runs the entirety of prehistoric cultural presence on the Plateau—with the possibility of later fakes, or forgeries—especially in the pictographs.

Human Presence on the Colorado Plateau

Clovis People

Figure 6 represents the documented localities of Clovis people. All but one of these localities reflects isolate surface finds. One locality (Davis and Brown, 1986) represents the lag remnants of a Clovis site where lithic manufacturing took place.

For a large geographic area deemed to be absent of late Pleistocene megafauna hunters by the "Plateau Myth," there is a surprising abundance of artifactual material derived from this early cultural manifestation. Several localities are proximal to the GSENM, which is indicative that such remains could also be discovered in the Monument.

Folsom People

Figure 7 provides a distribution map of documented Folsom

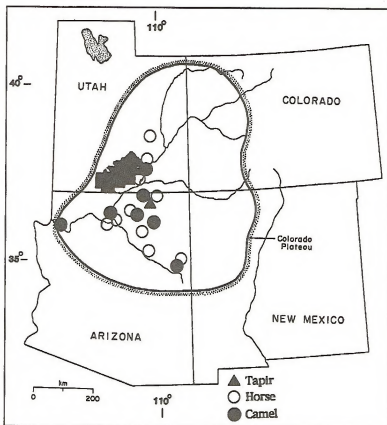


Figure 4. Documented localities for camels, tapirs, and horses on the Colorado Plateau.

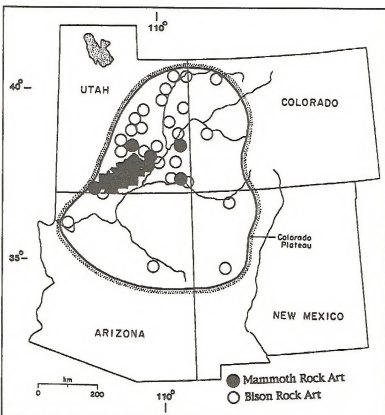


Figure 5. Documented localities for mammoth and bison rock art on the Colorado Plateau.

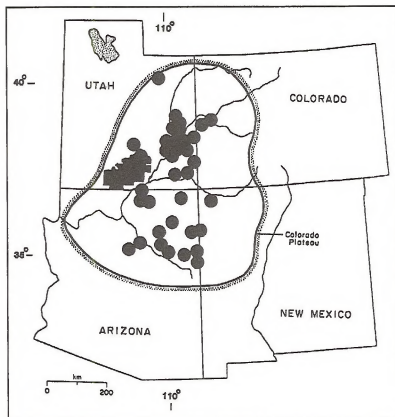


Figure 6. The locations of documented Clovis cultural presence on the Colorado Plateau.

localities. As with Clovis, all but two of the localities (Davis, 1985) represent surface finds of Folsom artifacts. Several of these localities are proximal to, or lie within, the newly created boundaries of the GSENM.

Plano People

The distribution of this more recent grouping of Paleo-Indian people is shown in Figure 8. Their distribution is generally more northerly, easterly, and southerly than the boundaries of the GSENM. The point to be made in this (and the preceding Paleo-Indian cultures) is that they were present on the Colorado Plateau, and evidently quite abundantly—just as were their major prey animals—mammoth for Clovis people, and bison for all groups.

Archaic People

Figure 9 provides a distribution map of areas containing Archaic localities rather than individual localities themselves. The combined populations of Clovis through Archaic peoples documents a high prehistoric/precereamic population density. Actually, the combined presence documents an interval of more than 9,000 years of aceramic prehistoric cultural presence that is rarely recognized, or researched, due to the preoccupation of Plateau prehistorians with the ceramic groups of the Anasazi. The GSENM has high potential for this aceramic cultural presence.

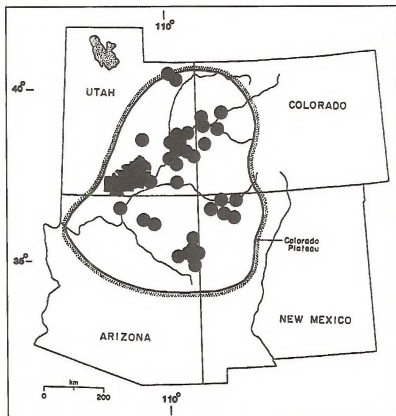


Figure 7. The locations of documented Folsom cultural presence on the Colorado Plateau.



The Shattering of a Myth

The documentation presented for Pleistocene megafauna (Figure 10) and Pleistocene and early Holocene peoples (Figure 11) of the Colorado Plateau destroys the "Plateau Prehistory Myth." There are at least 9,000 years of human presence and prehistory on the Colorado Plateau that is largely unrecognized, and certainly underresearched, due to an investigatory bias toward ceramic cultures. Even more impressive is the "post-dinosaur" presence of abundant Pleistocene large animals, also often unrecognized and certainly underresearched.

Additional Data Sets

In addition to these data sets, there is a large quantity of additional Quaternary information present on the Plateau, and certainly within the boundaries of the GSENM. Information in the form of packrat middens, pollen profiles, small mammal distributions, macrofloral remains, malacofauna (snails), paludal and lacustrine environments, alluvial terraces and aggradation/degradation sequences, plus a geochronologic reference framework, which contains all the data sets listed above. Plummer et al. (1997) may have recognized a paleoclimatic signal in Cl^{36} abundance in fossil packrat urine. This signal promises to be more sensitive than ice core data or radiocarbon data. The GSENM has great potential for this new field of paleoclimatic research.

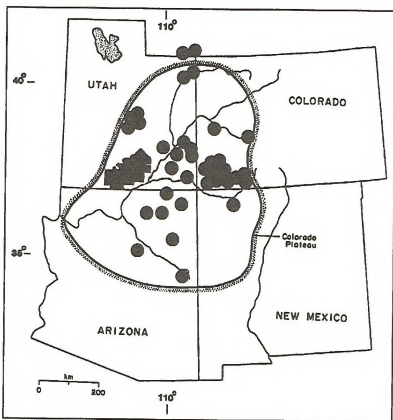


Figure 8. The locations of documented Plano cultural presence on the Colorado Plateau.

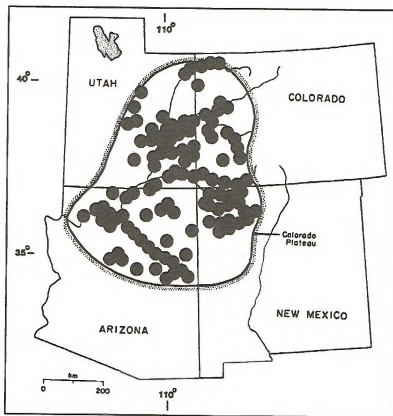


Figure 9. The locations of Archaic cultural presence on the Colorado Plateau.

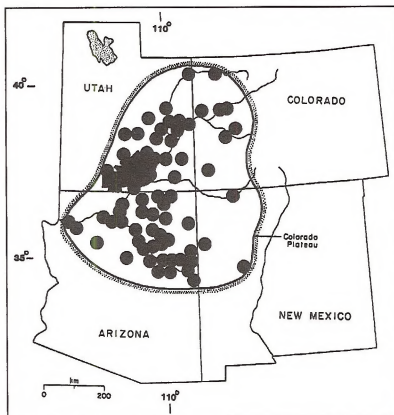


Figure 10. A combined plot of Quaternary megafaunal localities on the Colorado Plateau. (One dot may represent several species.)

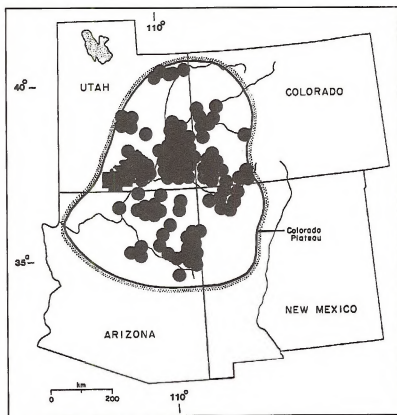


Figure 11. A combined plot of pre-Archaic cultural (pre-6,000 year B.P.) groups on the Colorado Plateau. (One dot may represent more than one cultural group.)

The Colorado Plateau is unique in its geology, temperature, and climate. Within it are storehouses of information that document physical, climatic, geologic, and cultural changes—all interrelated.

Paleoclimatic/ Hydrogeologic Data

There is a combination of unique paleoclimatic records preserved on the Plateau. Dung of extinct megaherbivores, packrat middens, and pollen promise an integrated model with high resolution (sophistication).

In addition, there is a geohydrologic data set. It is not as easily interpreted as the botanical evidence, but it, too, records climatic fluctuations. In the pre- ^{14}C era, geoscientists such as Bryan (1925), Hack (1942), Antevs (1955), and others provided geohydrologic models for preceramic temporal periods. Post- ^{14}C refinements of those models have been presented by Haynes (1968) for the Western United States, and Karlstrom (1984) for the Black Mesa region of Northern Arizona.

Of particular importance is the recognition of the fact that there is a cyclic change in climatic signals (and therefore in available moisture and the resultant plant cover). At present, there are groups who advocate eradication of cattle on public lands, and other groups who advocate preservation of sterile soil crusts. They blame erosion and pollution on the former, and the fragileness of nature on the latter.

What about the precattle, prehistoric cycles of aggradation



(deposition) and degradation (erosion) that are preserved in the alluvial record? Two basic causal forces initiate changes in geohydrologic processes: climate or tectonic uplift. Considering the Colorado Plateau for the last 2 million years, climate change has played the dominant role.

When present and future management policy is modeled from the "new conditions," the evidence and information from the "past conditions" is ignored; i.e., how did the "present conditions" get that way and is anything missing? The megaherbivores (including Anasazi, Archaic, and Paleo-Indian peoples) certainly caused modification of the environment, landscape, and pollution. It takes disturbances to break sterile crusts, to allow seeds to germinate. It takes herbivore intestinal tracts to spread seeds, as well as prepare some types of seeds to germinate. A management policy needs to consider all facets of a multifaceted gem—the natural environment.

Management Policies: "The Past is the Key to the Present (and Future)!"

Management policies within the GSENM must consider the prehistory of the land. Not just the European contact (historic context), not just the 2,000-year history (Anasazi/ ceramic), but the land and its flora and fauna as they evolved throughout the Tertiary and Quaternary periods of geologic time. A concept I continually run across from land managers is, "We plan to restore this _____ to pristine conditions." My response is, "Pristine *when*—100 years ago, 1,000 years ago, 10,000 years ago? Then, how do you know what pristine is? They are not all the same!"

I would like to encourage every entity involved with land management policy to read a paper written by Dr. Wayne Burkhardt, of the Idaho Forest, Wildlife and Range Experiment Station, University of Idaho, Moscow (Burkhardt 1996). He is addressing the Pacific Northwest and Intermountain West, but his reasoning applies just as aptly to the Colorado Plateau and to the Southwest.

His basic premise is that conditions at European contact were not pristine, nor the apex of landscape, floral, and faunal evolution for the past 40-60 million years. There had been more than 11,000 years of cultural interference with the biota and the environment. One of the large changes in that 11,000 years was the loss of large herbivores (megaherbivores), including mammoths, sloths, camels, horses, oxen (shrub and musk), Harrington's mountain goat, etc. (Table 2). Also, missing were/are the megacarnivores: teratons, condors, wolves, black bears, grizzly bears, and short-faced bears.

Those available ecologic niches were left—without replacement species—until the introduction of domestic animals by European settlers. Bison, elk, deer, moose, bighorn sheep,

Table 2. Mammalian (megafauna) biodiversity—Colorado Plateau.

Pleistocene		Holocene	
Mammoth	(<i>Mammuthus</i>)	Elk	(<i>Cervus</i>)
Mastodon	(<i>Mammuth</i>)	Deer	(<i>Odocoileus</i>)
Sloths	(<i>Glossotherium</i>)	Bighorn	(<i>Ovis</i>)
	(<i>Notharctatheraps</i>)	Coyote	(<i>Canis</i>)
Camel	(<i>Camelops</i>)	Bear	(<i>Ursus</i>)
Llama	(<i>Llama</i>)	Cats	(<i>Felis</i> , <i>Panthera</i>)
Horse	(<i>Equus</i>)	Wolf	(<i>C. lupus</i>)
Bison	(<i>Bison</i>)	Humans	(<i>Homo</i>)
Shrub Ox	(<i>Euceraetherium</i>)	Antelope	(<i>Antilocapra</i>)
Musk Ox	(<i>Symbas</i>)	Bison	(<i>Bison</i>)
Mountain Goat	(<i>Oreamnos</i>)		
Bear	(<i>Arctodus</i> , <i>Ursus</i>)		
Cats	(<i>Panthera</i> , <i>Leo</i> , <i>Felis</i>)		
Coyote	(<i>Canis latrans</i>)		
Wolf	(<i>Canis armbrusteri</i>)		
	(<i>Canis edwardii</i>)		
Humans	(<i>Homo</i>)		
Antelope	(<i>Stiloceras</i>)		
Tapir	(<i>Tapirus</i>)		



and modern mountain goats survived, often with reduced populations, reduced ranges, or both.

Based on the preceding information, as presented in this paper, I encourage the GSENM staff to adapt a management policy that addresses not only the present, or the 2,000-year prehistory—but one that stretches their conceptual limits to include the late Pleistocene and the entire Holocene. This will require multidisciplinary research or researchers. But, only in understanding the past, and how that background and those processes created the present, can we hope to gain an appreciation of the current environment and prepare for its future.

The past is the key to the present...and the future.

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A Historical Sketch of the Scientific Exploration of the Region Containing the Grand Staircase-Escalante National Monument

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For more than a century, the remote and unexplored regions of southern Utah and northern Arizona along the Colorado River have been a magnet for the scientifically curious. The area, which now comprises the Grand Staircase-Escalante National Monument (GSENM) (Figure 1), was the last region in the continental United States to be explored. In 1931, the great geologist Herbert E. Gregory wrote of the Kaiparowits Plateau:

In their traverse of the Colorado River and of the rim of the High Plateaus, the members of the Powell Survey

ABSTRACT

■ For more than a century, the remote unexplored regions of southern Utah and northern Arizona along the Colorado River have been a magnet for the scientifically curious. The region has a "rich history" as the Monument's proclamation declares. This is a history which was, for the most part, promoted by inquiring scientists and naturalists. John Wesley Powell explored the canyons of the Colorado River and sought to read "a Book of Revelation in the rock-leaved Bible of geology." Powell explored the southern edge of the Monument and the area along the Paria River, but his primary focus was on the Colorado River.

Powell's colleagues penetrated deeper into the region containing the new National Monument. Almon Thompson explored the northern edges of the current Monument boundaries in 1872. From the eastern slopes of Boulder Mountain, he mapped and named many of the main features in the Monument. The Escalante River was the last river mapped in the United States and the Henry Mountains were the last major mountain range. In 1875, G.K. Gilbert sought to understand the geology of the Henry Mountains. He explored the northern slopes of the Fifty-mile Mountain (The Kaiparowits) and had a closeup view of the labyrinth of canyons that drain into the Escalante River. Clarence Dutton from the Kaibab Mountain in Arizona saw and named the succession of giant geological steps, "The Grand Staircase," from the Vermilion Cliffs at the base to the Pink Cliffs at Bryce Canyon.

Despite their thoroughness, there was too much to explore and to write about. By the turn of the century, a new generation of scientist came to understand and unlock the secrets of this remote and intriguing land. The single most important was the U.S. Geological Survey geologist Herbert E. Gregory. Gregory devoted his professional life to writing and exploring southern Utah. His great studies also contained extraordinary historical sketches of the geologic science in the Grand Staircase-Escalante Monument region. His geologic studies were complemented by the pioneering work of Neil Judd in archaeology.



The work of Gregory and Judd led to recommendations that the region be set aside as a National Monument in 1935. The original proposal asked for nearly 7,000 square miles; an area which includes nearly all of the present Monument, Canyonlands National Park, and the Glen Canyon National Recreation Area. Because of political considerations and the potential for dams in Glen Canyon, the final recommendations were never made.

In 1956, Congress passed legislation for the construction of Glen Canyon Dam. The result was another round of scientific and historical studies. Jesse Jennings studied the archaeology of Glen Canyon and the surrounding areas, and Gregory Crampton studied and wrote the history of the region before it was flooded with the waters of Lake Powell.

Lake Powell brought further scientific studies to the region because it provided for potential water resources and an infrastructure of roads, power, etc., which made the development of natural resources, particularly coal, possible. The scientific studies of the Kaiparowits indicated it contained one of the Nation's greatest coal reserves. At the same time, the 1964 Wilderness Act brought the interest of the environmental groups and world awareness of the region's scenic and pristine beauty. With President Clinton's designation in September 1996, a new round of scientific studies of the region began. The new Monument offers the historian a wonderful place to study the history of science. Those seeking to use the Monument's great resources for study should understand some of that history.

outlined a large area between the Henry Mountains and the Kaibab Plateau within which the Kaiparowits Plateau is the dominating feature. Difficulty of access, dry climate, scant vegetation, small water supplies, and complete absence of human population prevented a study of this region under the conditions then prevailing, and trappers and prospectors who preceded and followed these early explorers were little interested in making detailed examinations of the sandstones that constitute most of the bedrock. Largely for these reasons the Kaiparowits region has long remained geologically unknown, and probably parts of it at least have been seen by white men only within the last ten years...Furthermore, the very fact that the existing knowledge of the region was meager made a strong appeal (Gregory and Moore, 1931).

Even today, one of the most attractive features of the GSENM is that it is still a relatively untouched region and it offers scientists

remarkable opportunities for detailed study of its archaeology, biology, geology, and paleontology. For the historian of science, the Monument provides a fascinating case study of an important place and the people who have sought to understand its secrets.

A Note on the Monument's Name

Perhaps it is not surprising that the new Monument received its name from work of early scientists. In 1875, Almon Thompson of the Powell survey suggested to a group of

Mormon explorers on the Escalante River that they call the river and any community that they might establish "Escalante." Thompson felt that the area deserved the name of the diarist of the first Spanish entrada into southern Utah. The men accepted his suggestion when the community of Escalante was established in 1877 (Gregory, 1939). Clarence Dutton, also of the Powell survey, in his classic work, *Tertiary History of the Grand Cañon District*, wrote as he stood on the north slopes of the Kaibab Mountain looking north:

Upon the extreme north is a series of terraces carved by erosion out of the Mesozoic and lower Eocene strata, which, covering all the region of the High Plateaus, suddenly terminate in a succession of high cliffs, dropping step by step to lower and lower formations, like a giant stairway (Dutton, 1977).

The 1882 description persisted, and geologists have been calling this striking geologic feature

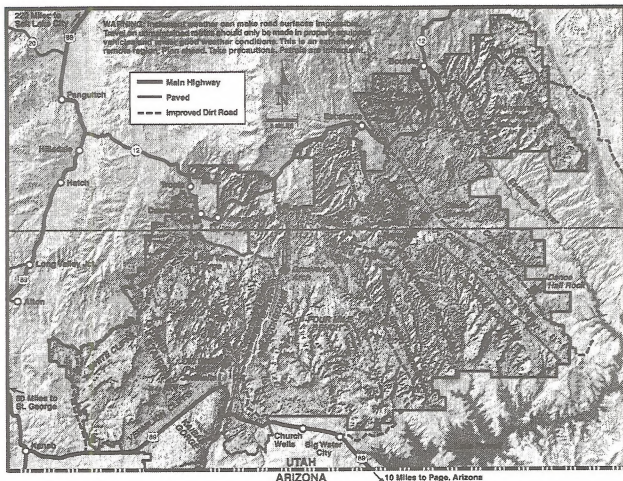


Figure 1. Grand Staircase-Escalante National Monument (map courtesy of BLM).

the "Grand Staircase" ever since. Whoever chose these historic names for the new Monument was familiar with these designations.

In designating the Monument, President Clinton's use of the Antiquities Act, which was passed by Congress in 1906 to protect cultural and scientific significant areas under government ownership, was unique. First, it was the single largest declaration (1.7 million acres) within the continental United States. Only the National Monuments set aside by President Jimmy Carter in Alaska in 1978 were larger (Congressional Quarterly Almanac, 1979). Second, the GSENM was the first National Monument to be administered by the Bureau of Land Management (BLM). In the past, only the National Park Service, U.S. Forest Service, and War Department have been responsible for Park and Monument administration (Lee, 1970). Third, and most controversial, was the manner in which the

declaration was made. No attempt was made to consult Utah State officials or congressional members (Lugwig, 1996).

Early Exploration of the GSENM

Scientific exploration of the GSENM region began with the first recorded passage through the southern borders of the Monument in late October 1776. The Dominguez and Escalante expedition, which left Santa Fe in the summer of 1776 to find a route to Monterey, described the natives (Paiutes) of the area in some detail. For the anthropologist, the Escalante journal provides the first closeup view of the Indians who inhabited the region. One recorded incident reveals some interesting relationships between the Paiutes (Sabnaganas) and their



neighbors. The fathers preached to the Indians, but the interpreter translated their message: "The Padre says that the Apaches, Navajos, and Comanches who are not baptized cannot enter heaven—and they will burn like wood in the fire" (Warner, 1976). The Paiutes were delighted with this since they had been excluded and their enemies condemned. After the Dominguez-Escalante expedition, the Spanish made no more attempts to enter the GSENM region. Their Mexican successors probably crossed the GSENM region on some of their journeys to California, but no physical descriptions except for their commercial concerns exist (Moody, 1963).

Mormon Exploration

The next recorded expedition into the GSENM region was an early Mormon group of explorers in the fall of 1854. Their principal interest was to locate usable natural resources and look for potential sites for the establishment of communities. The Mormons were keen observers of the country they visited and wrote detailed reports of their explorations. As this group journeyed across the southern edge and up the upper reaches of the Buckskin Gulch of the GSENM, they described some very interesting things. Their journalist wrote:

Amongst these mountains we saw many specimens of fine earthenware well glazed on both sides, body red beautifully painted in black & white in various figures....What changes have then occurred in these places?—here also we found large specimens of petrified wood, almost entire trees as hard as stone, and fine specimens of green paint- & beautiful red which, in my opinion, contains much quicksilver (Brooks, 1972).

The next major Mormon exploration of the region came with a military excursion into the area in 1866. The primary purpose of this expedition was to ascertain if there were places where the Colorado River could be crossed that were not already known (Woodbury, 1950). With this information,

action could be taken to guard against the loss of stock from Indian raids across the river. Recent Navajo raids into southern Utah were the primary concern at the time.

In August 1866, two companies were sent from St. George and Cedar City to look for these additional crossings. The St. George company, under the command of James Andrus, traversed Johnson Canyon, then traveled northeast up the western edge of the Paria River. The Cedar City company, under the command of Joseph Fish, met the St. George company on the Paria River near Cannonville. They explored the eastern edge of Bryce Canyon National Park and the headwaters of Bull Valley Gorge and Sheep Creek. The death of one of their party, Elijah Averett, by Indian ambush helps historians pinpoint their traverse since his grave is still well-marked. From the Cannonville area they headed east to the head of Potato Valley, and then to the top of Canaan Peak where they had a grand view of the Escalante River drainage. After a rugged descent down Alvey Wash to the Escalante River, the group crossed Boulder Mountain, then returned to Cedar City and St. George (Krenkel, 1970). The expedition rightly concluded that there were no practical crossings of the Colorado River in this region except for the well-known crossings at the future Lees Ferry and at El Vado de los Padres (Crossing of the Fathers). Jacob Hamblin and the Dominguez-Escalante party had already located these two important crossings.

This military expedition and the 1854 exploring party provided the fundamental information and guides for the Powell survey, who would soon enter the GSENM region. Chief among the Mormon scouts was Jacob Hamblin, Mormon apostle to the Indians. Hamblin had been in the 1854 exploring party and only sickness prevented his presence in the 1866 expedition. By 1863, he had completed a circuit around the Grand Canyon. He was thoroughly familiar with the southern region of the GSENM as a result of his work with the region's Indians (Corbett, 1968). Even though he was not with the 1866 expedition, by 1871 he had retraced much of that expedition's



journey. His knowledge of the region and the tributary canyons of the Colorado River brought him into the employ of John Wesley Powell when Powell secured funding for his Colorado Plateau survey beginning in 1871.

The Powell Survey: Mapping the GSENM Region

After Powell's successful, but hurried, descent of the Colorado River in 1869, he came back in 1871 with plans and financing for a 2-year exploration of the river and its adjacent canyons and mountains. Before he was finished, he and his men had spent most of the decade of the 1870's mapping, exploring, and writing about the last unexplored region in the country.

In 1871, the river survey traveled from Green River, Wyoming to Lees Ferry. Powell left the river party twice to arrange for supplies at various points along the route. At the mouth of the Dirty Devil River, Powell and his men stored a boat and a cache of supplies for a contemplated overland journey through an unmapped region north and west of the river. He left the river the final time at El Vado where his party was met by Jacob Hamblin with a supply train (Dellenbaugh, 1984). Powell sent his river party on to Lees Ferry and he traveled with Hamblin to Kanab. As a result, he became the first trained scientist to travel through a section of the future GSENM. However, he made no special mention of the region in his published reports. His primary concern at the time was to learn the fate of the three men who left his 1869 party in Separation Canyon on the western edge of the Grand Canyon. After journeying with Hamblin to the lower Grand Canyon region, he concluded that they were killed by Paiutes, and he set out to understand and map the regions around the Colorado River, an area which includes the GSENM.

During the decade of the 1870's, Powell and his survey crew explored and mapped much

of southern Utah and northern Arizona. In fact, it was their work that resulted in the actual location of the Utah-Arizona border, which was set by Congress with the passage of the famous Compromise of 1850. Since Powell was occupied with administrative duties and fundraising, most of the actual mapping and geological studies were left in the hands of his able brother-in-law, Almon Thompson. Of the many excursions into the Plateau region, Thompson directed four major excursions into the GSENM area.

His first expedition, and perhaps most famous, started in Kanab on May 29, 1872. The primary purpose of this foray was to travel across mostly unknown country to retrieve the boat that was left on the Colorado River at the mouth of the Dirty Devil River. Powell had sent Hamblin and Paryn Dods to scout a possible route the fall before. The route the party followed with Dods as guide led them up Johnson Canyon to Skutumpah, east to the western rim of the Paria River, north to present-day Henrieville, northeast to the head of Potato Valley and on to the head of the Escalante River, north across the eastern face of the Boulder Mountain, east through the Waterpocket Fold over the Henry Mountains, and southeast down Trachyte Wash to the boat on the Colorado River. The previous fall, Dods had supposed that the Escalante River was actually the Dirty Devil, which would lead them to the Colorado River. As soon as Thompson reached the Escalante area and surveyed it from the slopes of the Kaiparowits, he realized that they had not noticed the Escalante River the year before, and that the unknown mountains (Henry Mountains) and their boat and cache were yet a long way away. He sent part of his party back for additional supplies, and after considerable difficulty, the rest of his party arrived at the Colorado River and their boat on June 22. Thompson sent four of his men down the river in the boat, and he and two companions headed back to Kanab. Thompson made careful notes on the geology of the area and retraced his route back to Kanab, arriving on July 7, 1872. On the return, he took time to climb Table Mountain for geologic and geographic observations (Gregory, 1939).



Thompson's second expedition, from August 20 to September 1, 1873, explored and mapped the Paria River Canyon and the adjacent Cottonwood Wash along the Cockscomb. He clearly understood that the great geologic structure was a giant fold, and he called it the eastern edge of the Kaibab Fold. The short journey gave Thompson and his men the first geologic overview of the southern region of the future Monument, and they recognized that the white cliffs in the Escalante River region and those at the Cockscomb and in the Paria River were the same formation (Gregory, 1939).

Thompson's third major trip into the GSENM region came in the summer of 1875. He brought along a young, but promising, geologist from the Wheeler survey, Grove Karl Gilbert. After examining the geology of the Salina Canyon, the party headed for the Henry Mountains, where Gilbert would formulate his idea of "lacolith" and eventually produce one of geology's masterpieces, *Report on The Geology of the Henry Mountains*. To better understand the mountains, Thompson and Gilbert traveled south across the face of Boulder Mountain to the head of the Escalante River. They then traveled south along the edge of Fiftymile Mountain (Kaiparowits Plateau) to get a general view of the geologic structures surrounding the Henry Mountains. The group discovered and photographed the area, which was later called the Devils Garden (Gregory, 1939; Hunt, 1988). They also found coal in the Kaiparowits and described Chimney Rock and other geologic wonders on the south side of the Escalante River. They traveled as far as present-day Dance Hall Rock before they returned to their base camp on Boulder Mountain. On August 5, they met the exploring party, who took Thompson's advice and called the river and the town they established "Escalante" (Gregory, 1939). Thompson left Gilbert to finish his study of the Henry Mountains, a task that he continued into 1876. Interestingly, Mormon colonizers of southeastern Utah followed the route of Thompson and Gilbert on the south side of the Escalante River just 4 years later. The pioneering effort of the "Hole in the

Rock" expedition is legendary in the history of Utah as they opened a wagon route through one of the most rugged regions of the United States. The route proved to be difficult and was abandoned by 1881 (Miller, 1966).

After leaving Gilbert, Thompson visited Mormon settlements on the Sevier River for supplies, then headed for El Vado. His trip to the Crossing of the Fathers during the last 8 days of August 1875 enabled him to map the upper tributaries of the Buckskin Gulch, both Warm and Wahweap Creeks, and the south side of the Kaiparowits (Gregory, 1939). In addition to Thompson's studies and mapping, Clarence Dutton wrote two impressive volumes on the geology of the region surrounding the GSENM area. These two classics, *The High Plateaus of Utah* and *Tertiary History of the Grand Cañon* provide the modern reader with incredible descriptions of much of Utah's parklands in their virgin state. The Powell survey made significant pioneering studies of the geology of the plateaus, mountains, and streams of southern Utah and northern Arizona. The last unexplored and unmapped region of the continental United States, including the GSENM, had now been mapped and explored. The published reports of Powell, Thompson, Gilbert, and Dutton would be the basis for future scientific study of the region for the next century.

Herbert E. Gregory in the GSENM

Following the Powell survey, few scientific studies were made in the GSENM region. It would be the second decade of the 20th century before scientists would begin studying the area again. Mormon attempts to settle the region were slow. Except for a few settlements at the head of the Paria River, which survived by diverting water from the east Fork of the Sevier River, and Johnson Canyon on the west, the GSENM was somewhat hostile to human habitation. Mormon settlers did find and develop usable ranch lands in the area and



found resources like coal to use (Gregory, 1945). This relative isolation is what attracted USGS geologist, Herbert E. Gregory, to the Kaiparowits Plateau and eventually to most of the area within and surrounding the GSENM. Gregory would spend 40 years exploring, studying, and writing about the area.

After completing his classic study on the water resources of the Navajo Nation, Gregory turned to the least studied area of the region, the Kaiparowits Plateau. In the summer of 1915 he made an exploratory trip across the barren Plateau "to locate waterholes and to select areas where detailed study could profitably be undertaken" (Gregory and Moore, 1931). The successful accomplishment of his 1915 survey brought him back to the Kaiparowits for field studies in 1918, 1922, and 1924. With the able assistance of Raymond C. Moore, they published the results of their study in *The Kaiparowits Region*, U.S. Geological Survey Professional Paper 164 in 1931. One of the major features of the paper was a chapter on economic geology. Moore and Gregory concluded there was ample coal for a major commercial operation in the Kaiparowits region, but because of its remoteness, development of the coal would not come quickly. They also discussed the scenic arches and bridges of the Escalante River, those on the lower tributaries of the Paria, and the balanced rocks in the Rimrocks region.

Gregory's studies extended westward from the Kaiparowits in 1923 as he began his reconnaissance of the upper Paria River and Paunsaugunt Plateau. His geographic and geologic studies here continued until 1940. His published report primarily dwelt on the geology and geography of Bryce Canyon National Park, the upper step of the "Grand Staircase," and the upper Paria River and its tributaries, which drain the Park (Gregory, 1951).

Gregory's third major publication on the GSENM area dwelt on the geography and geology of central Kane County from Johnson Canyon to the Cockscomb. The outstanding geologic structures that he examined in this study included the Paunsaugunt fault, the

Kaibab upwarp (Kaibab Mountain), and the East Kaibab monocline (Cockscomb). He also discussed the petrified forest regions of the Monument in this area. After all his studies of the southern Paria River region, he had one major puzzling geologic question—why did the Paria River and its lower tributaries cut southeastward across the more resistant structures, instead of flowing southward down the less resistant House Rock Valley and onto the Colorado River? It all seemed so unnatural. He decided the strange erosional cuts of the lower Paria River were due to "wide-scale changes in stream habit" (Gregory, 1948).

Early Archaeological Studies

John Wesley Powell was very interested in ethnology and archaeology and established the Bureau of Ethnology after he had left his work along the Colorado River. His pioneering studies in archaeology, like his geological studies, concentrated on the Grand Canyon region (Stegner, 1953). The first serious and professional study on the edges of the GSENM was done by Bryon Cummings and his student, Neil Judd. Judd completed a major study on the Paria Plateau in 1920.

The first two archaeological expeditions into the GSENM came in 1928. The Peabody Museum at Harvard University conducted a reconnaissance of the Kaiparowits Plateau under the leadership of Donald Scott. About a month later, Clyde Kluckhohn led a group into the same area. He reported seeing ruins scattered all across the Plateau. His discoveries were published in a popular book, *Beyond the Rainbow* (Kluckhohn, 1933).

The first expedition into the west side of the GSENM was conducted by Julian H. Steward from the University of Utah. Steward's 1932 party recorded 142 sites in Johnson Canyon and along the Paria River (Steward, 1941). The sites were later classified as Virgin Anasazi. A third Kaiparowits reconnaissance



came in 1935 as part of the Rainbow Bridge/Monument Valley expeditions. These scientific investigations occurred every summer from 1933 through 1938. The 1935 archaeology group walked up Rock Creek Canyon from Glen Canyon to the top of the Plateau, and in a very short time, recorded over 100 sites (Christensen, 1987).

The 1935 Proposed Escalante National Monument

Utah was almost entirely dependent upon use of its federally administered lands to base a recovery program for the Great Depression in the 1930's. One of the many proposals for such land use was the 1935 suggestion that 6,968 square miles be set aside as the Escalante National Monument (Richardson, 1965). The proposed Monument included much of the GSENM, parts of what would become Capital Reef and Canyonlands National Parks, and the region north of the San Juan River. This was 8 percent of the Utah land mass, over 4.45 million acres. The political leaders of Utah, led by Governor Henry Blood, at first were favorable, but eventually became active opponents of the proposal, even though the size of the proposed Monument was reduced to 2,450 square miles. Their main concern was the future use of the water of the Colorado River. The construction of Boulder (Hoover) Dam on the lower Colorado and the potential for resource development with a Glen Canyon Dam resulted in delays on the Monument proposal. With the advent of World War II, even allies of the proposal decided not to pursue it, and the idea of a new Monument was dropped.

Publicity from the Monument proposal and the discovery of a very large natural bridge (Gregory Natural Bridge) in the lower Escalante River in 1940 by a Colorado River rafting party brought national attention to the scenic value of the GSENM area. Local naturalists

like Edson Alvey of Escalante had discovered and named many of the numerous arches, waterfalls, and other scenic wonders (Woolsey, 1964). As a result of this publicity, National Geographic sent a crew to the region in 1948 to photograph and explore the country's wonders. Their expedition took them into the scenic heart of the GSENM. After photographing and measuring the size of the Butler Valley Arch (span 99 feet and height 152 feet), they named the unique double arch after the Society's President, Gilbert Grosvenor. It has been called the Grosvenor Arch ever since. The group also explored the Hole-in-the-Rock, Calf Creek, and Crossing of the Fathers, and they examined some of the arches in the Escalante River. The expedition's report, with color photographs, was published in the September 1949 issue of *National Geographic* magazine. *National Geographic* explorers featured the Escalante River and its wonderful arches two additional times after 1948 (Moore, 1955; Schneeberger, 1972). The construction of Glen Canyon Dam (1957 through 1963) brought additional publicity to the GSENM area and another wave of scientific studies to understand its unique wonders.

Glen Canyon Salvage Project

After the construction of Boulder Dam (1935), Parker Dam (1938), and Davis Dam (1953) on the lower Colorado River, the Bureau of Reclamation looked for storage reservoirs and power generating plants on the upper Colorado River. In April 1956, Congress authorized the construction of four new dams: Navajo Dam on the San Juan River, Curecanti Dam on the Gunnison River, Flaming Gorge Dam on the Green River, and Glen Canyon Dam on the Colorado River. The Glen Canyon Dam would back the waters of the Colorado River 183 miles from the dam and flood 150,000 acres in the Glen Canyon region. The principal concern for the four construction projects was that many yet unexplored archaeology sites would be lost after the dams



were complete. As a consequence, the Upper Colorado River Basin Archaeology Salvage Project was born. The greatest amount of work for scientists investigating the soon-to-be-flooded regions was at Lake Powell (Meusel, 1956).

At Glen Canyon research contracts were let by the National Park Service for salvage projects to the University of Utah and the Museum of Northern Arizona. The area south of the Colorado River and along the San Juan River was assigned to the Museum of Arizona, and the area north of the Colorado River was studied by the University of Utah. Because the GSENM was in the University study area, the results of their work are important for the history of scientific research in the Monument.

Dr. Jesse D. Jennings, University of Utah archaeologist, directed the research for Utah. He would write later: "As a summary, I suggest that in virtually any detail, and certainly in overall results, emergency salvage archaeology is superior to most other work done in America" (Jennings, 1966). The University's studies were not confined to archaeology, but also made important contributions in history and biology. Thirty major publications and a summary paper (nearly 6,000 pages) came as the result of their research during 1957-1963. A number of their publications dealt directly with the GSENM area. The work of Gregory and Charles B. Hunt provided the basic geology for the salvage project (Jennings, 1966).

Of the 30 research papers, 4 were studies in biology. Professor Angus M. Woodbury directed the biological research. Interestingly, Woodbury directed the biological research for the Rainbow Bridge-Monument Valley expeditions more than 20 years before. In 1957, Woodbury and his team of biologists made a preliminary survey of the work that had been done in biology in the Glen Canyon region and proposed a program of further studies. These proposals included a general reconnaissance of the area and an "investigation of the biological resources available to ancient people in this ecologically hostile region" (Woodbury, 1958). The general field work resulted in the

identification of numerous plants and animals in the Glen Canyon area and along its tributaries. Woodbury's *Notes on the Human Ecology of Glen Canyon*, published in early 1965, about a year after his unfortunate death in an automobile accident, provided important work for archaeologists to understand ancient peoples of the entire Southwest.

History was the subject of 8 of the 30 Glen Canyon Series publications. This work was directed by C. Gregory Crampton, professor of history at Utah. Four of the papers dealt with historic sites on the Colorado and San Juan Rivers. Portions of this research were published in popular form for Lake Powell boaters (Crampton, 1988). The other four research papers are of greater concern for GSENM investigators. Leland H. Creer authored two: *Mormon Towns in the Region of the Colorado* and *The Activities of Jacob Hamblin in the Region of the Colorado*. The two studies were published in 1958 as numbers 3 and 4 of the Glen Canyon Series. Robert B. Stanton investigated the mining history of the area in *The Hoskaninni Paper, Mining in the Glen Canyon 1897-1902*. Crampton's contribution dealt with the entire history of the Glen Canyon region. His important study was subsequently published in 1964 with extraordinary photographs and a detailed bibliography in *Standing Up Country* (Crampton, 1983). It is a must for anyone interested in the history of the Colorado River, Glen Canyon, and the GSENM region. In his summary, Jennings said of the history projects that total gains in knowledge in history were greater than in any other area of the salvage project and that "now it is possible to say that for the Glen, Cataract, and San Juan canyons the historical data are richer than for any other river in the west" (Jennings, 1966).

Sixty percent, or 18 of the Glen Canyon salvage project publications dealt with archaeology. Professor Jennings directed this work as well as the overall project. Several books could be written on the scientific results of the work in archaeology. In addition to annual reports on excavations for the years 1957-1962, and survey reports on archaeology work in the



area, the Utah team produced mountains of data on many Glen Canyon archaeological sites. Glen Canyon could not be understood in a vacuum, so additional studies were necessary to correlate their work with work done throughout the Southwest. In particular, their excavations and studies of the Kaiparowits Plateau and the Escalante River are important for the archaeology of the GSENM. The excavations and report at the Coombs site in Boulder would lead to the establishment of Anasazi State Park in 1960 (Lister and Lister, 1961). Concerning the Escalante River archaeology, Jennings said it was a miniature of the Glen Canyon system (Jennings, 1966).

Study of the Kaiparowits was undertaken since it was on the boundary of four important ancient cultures: the Virgin Anasazi to the southwest, Kayenta Anasazi to the southeast, Mesa Verde Anasazi to the east, and Fremont to the north. The excavations on the Kaiparowits established that its inhabitants were predominately Kayenta Anasazi who occupied the Plateau during the general period from 1050 to 1250 A.D. Each culture is defined by the type of ceramics they use, their domestic architecture, their kivas, and the mode of their burials. The archaeological work in the Glen Canyon and the adjacent GSENM was a significant contribution to the understanding of archaeology of the entire Southwest.

Resources for Power

With the construction of Glen Canyon Dam, suddenly the GSENM region was of considerable interest to a number of commercial entities. The dam brought an important infrastructure to the area. The remote region soon had good roads, and just as important, power and water. The future looked bright for development of the power resources of the region. The reports of Gregory and others highlighted the potential for development of coal and oil deposits in the Kaiparowits and Circle Cliffs. A new set of scientists came to the GSENM region to establish the feasibility of such development.

The first oil well to be drilled within the GSENM was completed in November 1921 by the Ohio Oil Company. It was a dry hole. The first significant show of oil came in 1948, when the California Company recovered oil in the Upper Valley area southwest of Escalante (Kunkel, 1965). By 1958, Edgar B. Heylman, consulting geologist, reported that even though the Kaiparowits had not sufficient tests to prove or disprove its merit as a commercially oil-productive region, there were still a number of anticlinal features that have not been drilled for gas or oil, and stratigraphic conditions are favorable for petroleum production at many localities (Heylman, 1958). The interest in oil has continued into the 1990's, and Conoco Oil, with permits prior to the creation of the GSENM, was granted rights to drill in September 1997 (Brown, 1997). At the time of the creation of the Monument, 90 oil leases were held by various corporations and individuals (Allison, 1997).

The extent of the coal deposits in the Kaiparowits became general knowledge after the studies by Gregory. Because of the ruggedness and isolation of the region, little was done towards commercial development of coal with the exception of very small mines near Mormon communities on the edges of the Plateau. With the completion of the Glen Canyon Dam and the power plant, things changed quickly. In addition to roads, water, and power, new transmission lines for the dam's power plant made the possibility of a coal fired power plant at the base of the Kaiparowits an interesting attraction for many. By 1961, over a dozen major coal firms and individuals had leases or prospecting permits on over 200,000 acres in the Kaiparowits Plateau coal field (Doelling and Graham, 1972).

After the early investigations in the area, it became apparent that the Kaiparowits was the largest coal field in the southwestern United States (Doelling and Graham, 1972). Estimates ranged from 5 to 15 billion tons of marketable coal. One of the major concerns was that to obtain the coal, it would have to be deep-mined. The studies in the 1960's led to the recommendation that a coal-fired



power plant be constructed in the Kaiparowits region. Early estimates indicated that such a facility could be up and running by 1980. The National Environmental Policy Act, which was signed into law on January 1, 1970, delayed the construction of the 3,000-megawatt plant. During the first 5 years of the 1970's, an extensive study was made to assess the impacts the proposal would have on the Kaiparowits region. The final impact statement was published in six large volumes (3,600 pages) in 1976 (USDI, 1976). Environmental groups delayed construction of the proposed facility and the mining of coal (USDI, 1976). With the Presidential proclamation in 1996, a power plant in the Kaiparowits region or the transportation of coal to a power plant in another area does not seem likely.

When the Monument was created, another round of scientific studies were initiated. The Utah Geological Society published three preliminary assessments of the energy and mineral resources, archaeology resources, and paleontologic resources within the GSENM (Allison, 1997; Madsen, 1997; Gillette and Hayden, 1997). Science studies and research were encouraged in the Monument proclamation. One result of this renewed interest was a symposium on science in the GSENM, in which three scientific field trips and over 50 scientific papers were presented on the new Monument. It was sponsored by the Utah State Advisory Council for Science and Technology, Southern Utah University, and the Bureau of Land Management.

The remoteness of the area in the GSENM has attracted scientists for more than a century. It has become one of the most studied areas in the United States. The history of that undertaking is perhaps one of the important stories in the history of science in America.

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Monitoring and Modeling the Weather and Climate of the Grand Staircase-Escalante National Monument

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ABSTRACT

■ The physiography of the Grand Staircase-Escalante National Monument leads to large spatial variations in precipitation that affect the ecological communities within the Monument. Many Federal and State agencies collect weather reports around the western United States. Surface observations from a variety of networks in Utah and surrounding states are obtained, processed, and displayed at the University of Utah in order to determine the temporal and spatial evolution of weather and climate in the Intermountain Region. Few stations report weather information routinely near the Grand Staircase-Escalante National Monument. Automated weather stations that can be accessed hourly by the National Weather Service should be installed in the Monument. These weather stations would contribute to the protection of life and property in the Monument.

Research is underway at the University of Utah to study the weather and climate of the Intermountain West. The National Oceanographic and Atmospheric Administration (NOAA) Cooperative Institute for Regional Prediction was established during 1996 to foster a broad program of research aimed at improving weather and climate prediction in regions of complex terrain, with emphasis placed on weather and climate issues of the Colorado River Basin and other regions of the western United States. The physiography of the Grand Staircase-Escalante National Monument (GSENM) leads to large spatial variations in precipitation: arid valleys are interspersed between mountain ranges that receive significantly larger amounts of precipitation. Monitoring and predicting these large gradients in precipitation remains difficult.

Monitoring

Many State and Federal agencies collect weather reports around the western United States. For example, surface observations from a variety of networks in Utah and surrounding states are obtained, processed, and displayed at the University of Utah in order to determine the temporal and spatial evolution of the weather in the Intermountain Region. These surface observations comprise the Utah Mesonet (Stiff, 1997). Graphics from the Utah Mesonet are accessible via the Internet either at the Salt Lake City National Weather Service (NWS) Forecast Office (nimbo.wrh.noaa.gov/Saltlake/slc.noaa.html) or the University of Utah (www.met.utah.edu).

Figure 1 depicts the stations that comprise the Utah Mesonet. Not all of these stations report

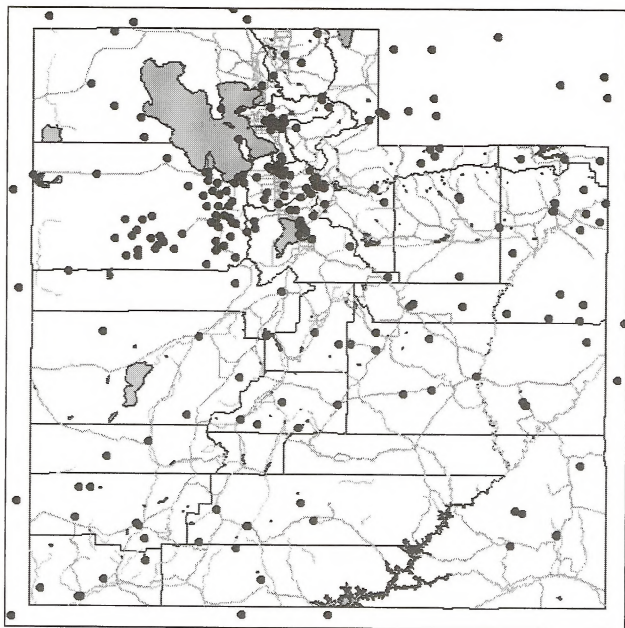


Figure 1. Locations (denoted by dots) of stations that comprise the Utah Mesonet.

weather information at the same time. Roughly 200 stations report weather conditions at least once per hour on a regular basis.

Each observational network is designed to meet the needs of the agency that installed it. For this reason, the types of weather parameters, the reporting interval, the level of quality control, and the frequency at which the observations are available vary considerably. For climate studies, greatest attention has been placed on daily precipitation and daily averaged temperature determined from the minimum

and maximum temperatures during a 24-hour period.

An example of the output available from the Utah Mesonet is shown in Figure 2. The hourly weather conditions (temperature and wind speed) during October 1997 are shown at Telegraph Flats (TFR), a station located in the GSENM. A large diurnal variation in temperature is evident, as well as the occurrence of storms that brought cooler temperatures and higher winds to the region.

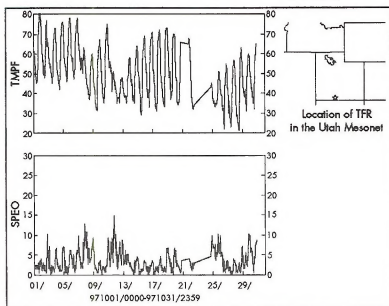


Figure 2. Time series of temperature (top panel, in °F) and wind speed (lower panel, in knots) during October 1997 at Telegraph Flats in the GSENM. This station is operated by the Bureau of Land Management.

Figure 3 shows the monthly average total precipitation at Escalante based on the period 1901-1997. This figure was obtained from a World Wide Web page developed by researchers at the Western Regional Climate Center at the Desert Research Institute. The largest amount of precipitation falls on average during August as a consequence of the summer monsoon. The Utah Climate Center, Utah State University, also provides climatological information for the stations near the GSENM.

To improve protection of life and property, Zion and Capitol Reef National Parks have cooperated recently with the National

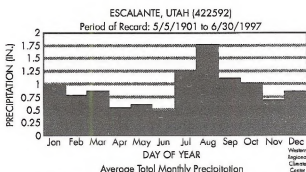


Figure 3. Monthly climatology of precipitation (in inches) at Escalante based on daily weather observations from 1901-1997. This figure was created by researchers at the Western Regional Climate Center, Desert Research Institute.

Weather Service to install automated weather stations that report current weather conditions several times per hour. Lightning storms, flash floods, high winds, and winter storms are some of the hazards that occur frequently in the GSENM. One or more additional automated weather stations should be placed in the GSENM to help monitor and improve prediction of severe weather events.

Modeling

Numerical prediction of precipitation in dryland regions of the western United States remains a difficult problem. The large variations in observed precipitation as a function of location and elevation are difficult to capture in weather and climate prediction models. The level of detail of the underlying terrain controls, to a large degree, the success of a model to simulate winter orographic precipitation. For example, the Eta model of the National Centers for Environmental Prediction (NCEP) is currently run operationally at 48-km and 29-km horizontal resolution. The 48-km version captures the broad features of the mountains in the western United States, while the 29-km version resolves adequately major mountain barriers, such as the Sierras and Rockies. However, the narrow mountain ranges of the GSENM are not captured by either operational versions of the model. A nested version of the Eta model at 10-km resolution has been tested at the NCEP. In addition, many research groups in the western United States are performing regional forecasts at 2-25 km. Computer resource limitations require that as the horizontal resolution is reduced in order to capture mesoscale and local weather and climate features, the horizontal domain must be restricted drastically in order to complete the forecast in a reasonable length of time.



Research is underway at the University of Utah to compare operational and experimental forecasts of precipitation over the western United States. Much of this work is available online at www.met.utah.edu. Hourly and daily records from the NWS and Colorado River Basin Forecast Center are used for verification of model forecasts at 6- and 24-h intervals. Sensitivity to terrain resolution and differences in model design are being documented. Physical parameterizations in the model that are designed to simulate convective and radiative processes control, to a large degree, the success of models to simulate summer season convective precipitation in the GSENM.

Considerable debate exists in the atmospheric modeling community over the direction in which the greatest improvements in forecast

skill are likely to develop in the next decade. One view is to continue to reduce the horizontal resolution of operational models to 1 km. Most significant features of the landscape would be captured at that resolution. The other view is that the potential gain in skill arising from high spatial resolution is offset by error growth arising from initial uncertainties. This error growth can overwhelm the skill of the model's forecast after 24-36h.

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Learning from the Land: Innovative Approaches to Utilizing the Grand Staircase- Escalante National Monument as an Outdoor Laboratory

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ABSTRACT

■ Geology, ecology, paleontology, archaeology, cultural history, and biological sciences are the base resources for education/outreach programs that focus on the Grand Staircase-Escalante National Monument. To facilitate the requests of local and area school districts, the Bryce Canyon National Park Education/Outreach Program has responded to the great interest expressed by educators and students about the Monument by utilizing several innovative learning approaches.

Grade-appropriate classroom programs have been developed and begin with instruction, games, demonstrations, and team-building activities that get students excited about the geological and biological sciences. The classroom activities are followed by field trips to different locations within the Monument to observe and practice conservation and scientific principles in an outdoor laboratory setting. Programs and field trips are conducted using a diverse pool of human resources including trained subject-matter experts, USGS personnel, university faculty, and other experienced educators. Formal programs such as *Intrigue of the Past* and *Project Wild* have also been incorporated into the curriculum.

To further assist educators in teaching about the geological, paleontological, and biological resources of the Grand Staircase-Escalante National Monument, a *Geo-Detective* learning series has been developed. The *Geo-Detective* program is structured around core curriculum concepts and lessons that build deductive reasoning skills. Educators and learners are provided with a "discovery chest" that contains teaching kits, specimens, analytical equipment, and applicable lessons that focus on geology, paleontology, hydrology, botany, biology, and astronomy.

Through our established working relationship with Southern Utah University (SUU), we provide a highly successful field seminar course that educators can take for needed academic credit. Since the inception of the field seminar series, we have focused on the Grand Staircase and Colorado Plateau region. Future



field seminar programs have been planned for the Great Basin region and Canyonlands of southeastern Utah. The success of the course can be directly attributed to the dedicated SUU geology and biology professors who participate in the program.

Field seminar courses allow teachers to interact with the Monument resources and develop and construct their experiences into a positive teaching tool for their students. The Education/Outreach Program is also designed to promote a greater understanding of geologic and biological concepts and provide a sense of appreciation and stewardship for the resources of the Monument.



The Grand Staircase-Escalante National Monument Environmental Intelligence Applications Program Study

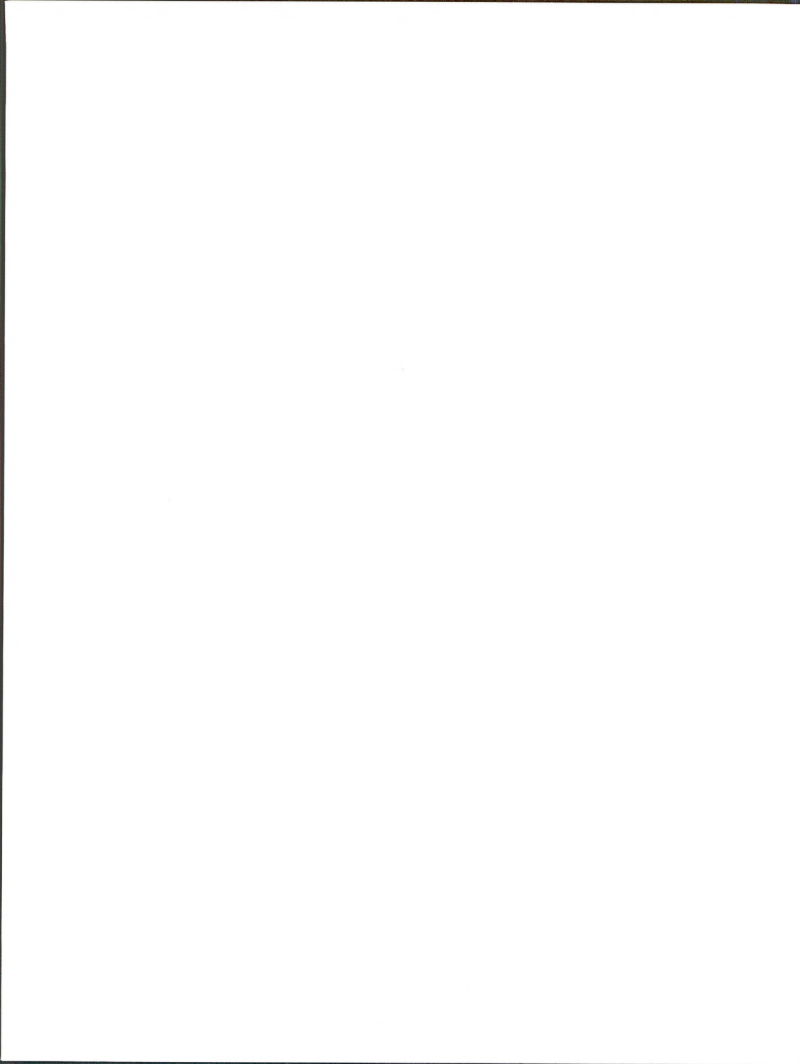
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ABSTRACT

■ In the fall of 1992, Albert Gore, who was then a Senator, recognized the potential utility of using intelligence capabilities for civil applications. The Environmental Task Force (ETF) was created to provide a vehicle to implement these capabilities, and a panel of 70 U.S. environmental scientists, identified by the name MEDEA, was subsequently convened to provide continuing scientific expertise to intelligence community efforts related to the environment.

In 1996, the ETF was renamed the Environmental Intelligence and Applications Program (EIAP). Under EIAP, MEDEA has undertaken an additional role as an advisor in the area of optimizing sensors and developing sensor strategies for environmental intelligence applications. The objective of the current EIAP studies is to identify and investigate new, improved, or modified sensor dual-use capabilities to provide environmental intelligence from classified overhead, airborne, or in-situ systems.

The Grand Staircase-Escalante National Monument Environmental Intelligence Applications Program Study is one of the currently authorized EIAP projects. Data derived from National Technical Means (NTM) will be used to inventory natural resource values within the Monument, including springs, archaeological sites, and geological features. The data will also be used to identify potential safety hazards, such as abandoned mine shafts and adits and underground coal fires.





Considering the Role of Science Within the Policy and Planning Process for the Grand Staircase-Escalante National Monument

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It is important, at times, to consider your work and how it fits within the context of which it is a part, because from self-reflection often comes learning. This symposium has provided such an opportunity. The newly established Grand Staircase-Escalante National Monument will continue to offer similar opportunities in the future.

Consider that the symposium's context stems from the September 18, 1996, Presidential Proclamation establishing Grand Staircase-Escalante National Monument under authority of the Antiquities Act of 1906 (16 U.S.C. 431). When President Clinton established the new Monument, he also began a policy and planning process by directing the Secretary of the Interior to charge the Bureau of Land Management (BLM) with administering the area and to complete a management plan within 3 years. BLM staff members, as they have progressed in their planning effort, have made clear that opportunities for significant

ABSTRACT

■ Science can play many roles within a participatory effort to manage public lands. Scientists willing to reflect upon those possible roles can advance science, their careers, and individual management efforts. Other authors have suggested similar ideas and some, especially natural scientists, offer especially compelling arguments. This paper argues that a policy process is strongest when it integrates physical, biological, and social science and, by extension, scientists have much to gain by engaging in a participatory and collaborative approach to planning. Substantiating the argument is a project, described here, that occurred in Great Smoky Mountains National Park beginning in late 1994. The case study compares well to the current policy process for the Grand Staircase-Escalante National Monument. To provide context for the case study, the paper begins by introducing an understanding of *policy process* and seven key ideas that follow from that understanding. This conception of a policy process also provides a framework to describe the case study, functioning as a flexible guideline, not sequential steps.

public involvement, and for participation of Tribal, State, and local governments, will occur as part of this process (USDI-BLM, 1997). Accordingly, we might consider the natural science topics of this symposium as they fit into the larger context of a participatory planning and policy process for a newly designated National Monument, a process with the goal of serving as "a model of creative thinking and collaborative planning" (USDI-BLM, 1997).

One Understanding of a Policy Process

Stated most generally, a *policy process* is the process of formulating and implementing



policy. There are, however, several definitions of *policy*. One is that policy is the intent to address a perceived problem, as when an agency such as the BLM intends to protect objects of scientific or historic interest within a particular area while recognizing valid and existing rights of others. In this sense, the Presidential Proclamation, which expresses this very intent, is a statement of policy.

Another definition of policy is a standing decision, as when the agency makes decisions about how to protect those objects of interest in light of valid, existing rights. One result of the BLM's planning work for the new Monument, for example, will be policies—standing decisions—for how the agency will manage this area on a daily or ongoing basis.

For this paper, however, perhaps the most interesting definition is that policy is the effective result of "what is intended" and "what actually happens." This understanding of policy reflects that an agency's intentions and standing decisions are tempered by, among other things, whether it has funding to accomplish what is intended, personnel to enact decisions, and stakeholders who will defer to those decisions. Accordingly, a policy process, then, should serve as a means to address both the formulation and the implementation that, in combination, determine policy.

This understanding of *policy* and *policy process* suggests several interesting implications to explore during this paper. One standing question that remains, however, is how might an actual policy process look if it reflects this general understanding of policy and policy process.

Six Components of a Policy Process

Brunner (1987) and Clark (1992) offer some structure for the admittedly abstract understanding of a policy process just established. They suggest there are six basic components.

These components are not steps to take in sequence. They are perhaps most helpful when you think of them as integrated components or phases. For example, addressing any single component is helped by understanding and considering each of the others, an idea also suggested by Renn et al. (1993) and Clark (1992). The following six components provide a structure for presenting the case study later in this paper. In each component, science and scientists can play a role.

The first component of a policy process is *initiation*. The process is initiated as people recognize that a problem or situation needs attention. Initiation quickly turns to the second component, *estimation*. Here, participants work to understand the problem or situation from all relevant perspectives by identifying issues and concerns, as well as any restraints or barriers to dealing with them. During estimation, the policy process also seeks to identify opportunities for addressing issues or concerns in light of identified barriers. As the case study will show, a participatory approach to the policy process can help reveal relevant issues, concerns, and barriers in a thorough, meaningful, and timely manner.

The third component is *selection*, which involves choosing an action. While engaged with this component, participants in the policy process might clearly establish what it is they are trying to accomplish. From there, they can take steps to identify actions that seem most likely to work and feasible to implement. It is important here to recognize and consider the likely consequences of each separate action and of the actions cumulatively.

The fourth and fifth components are quite related and essential to any process intended to remain flexible and adaptable to inevitable changes in the situation. *Implementation* follows selection and, defined most generally, involves taking those selected actions. *Evaluation*, the fifth component, follows implementation. During the evaluation phase, the policy process assesses whether selected and implemented actions are moving the



situation in a desired direction, as defined during earlier phases of the policy process.

Termination is the final component or phase of a policy process. It occurs when the actions are judged no longer necessary or are not accomplishing what was intended. A terminated policy process is not necessarily a success or a failure. It may only mean circumstances are right to try something else, or it may mean the situation has changed and there is no need for any more work to address what was perceived earlier as a problem. An adaptive management effort will apply a policy process that anticipates the conditions under which termination is most appropriate and attempt to describe those conditions. In a sense, because one policy process may evolve into another, termination, oddly enough, can mean a beginning or continuation instead of an end.

Seven Key Ideas that Follow from this Understanding of a Policy Process

The conception of a policy process, as just described, suggests several key ideas or implications. Seven specific implications are most relevant to the case study and to any consideration of the role of science within such a policy and planning process. The relevance of these implications also likely extends to the new Monument.

The Policy Process is a Supraorganization

Any policy process that involves multiple groups, organizations, or individuals is, at a broad scale, a supraorganization. This means we can think about it as an organization of organizations and we can learn from and apply knowledge and ideas found in writings about organizational behavior and management, an idea discussed further by Wheatley (1994).

One key point associated with this observation is that, because policy processes are organizations of interested, involved, or affected people, we should think beyond those who traditionally make decisions and focus instead on all those who have a stake in the decision (Clark, 1992). Managers, bureaucrats, and scientists are not the only people involved in the policy process. Those who must live with a decision also affect its outcome by, for example, whether they understand and comply with it. Because people outside the traditional decision process affect the outcome, policy processes can gain by involving those people, learning from their ideas, sharing with them the knowledge and expertise of traditional participants, and seeking to anticipate and address their concerns where possible.

Another point to consider is that limiting participation can reduce needed support no matter how thoughtful or well-intended the policy. Individuals or groups left out of the process can feel ignored or disenfranchised and see no reason to support the resulting policy. They may actively work to counter the policy. Furthermore, limiting participation can lead to a policy that does not reflect relevant issues or concerns, thus the resulting policy is based on incomplete information and better decisions are certainly possible.

On the other hand, expanded participation can lead to greater understanding among participants, a benefit to scientists who participate. For example, Manning (1995) found that, during participatory policy processes of the U.S. Forest Service, scientists and managers are better able to understand complex situations. Likewise, other participants are more likely to trust and request scientifically derived information and appreciate scientists' and managers' professional experience and knowledge. What appears to happen is that these other participants have an opportunity, by participating in the policy process, to better understand the situation, offer their knowledge, and buy into the result. In much the same way, scientists and managers are likely to find their understanding expands from knowledge contributed by these additional participants.



Thinking About Process Separate From Content Is Helpful

Some insights are most apparent when we see a difference between the *process* that goes into producing policy and the policy that is the *content* or result of the process. Seeing this distinction allows us to separate “how to decide” from “what to decide,” two different questions clearly quite related. Saying this another way, a policy process amounts to “making decisions,” a phrase with two parts worth considering: “making” and “decisions.” Both are important and so is the interaction of the two.

An important implication for scientists is that science can most contribute to meaningful content when scientists assist in the process (Brunner, 1987; Clark, 1992). Consider a policy that lacks support because there was not support or trust for the process that produced it. Scientists who wish to see a policy that has broad support and meaningful content can first work to see that the decision process itself attracts support and incorporates as much relevant knowledge as possible.

One way of ensuring that scientific knowledge plays a meaningful role in policy is for scientists to play a meaningful role in the policy process, much as Manning (1995) found. Similarly, if we want our concerns about conserving opportunities for scientific study reflected in the eventual policies for managing the new Monument, we need to become and remain involved in the policy process and encourage an open and participatory approach to decisions.

A Policy Process Is Based Upon Integration, Not Sequence

People are likely to support a process that integrates available information in pursuit of better decisions, as opposed to excluding potentially helpful sources of information, an idea Wheatley (1994) discusses in more detail. Such support occurs because an integrated approach is intuitive, inclusive, and makes sense.

Policy process components, as described earlier, are not steps to follow; they are integrated ideas, a point further discussed by Clark (1993). For example, it is often helpful to consider questions related to *evaluation* even while *estimating* the problem, as when scientists are available to describe current evaluation procedures for estimating a problem and its dimensions. Similarly, scientists' knowledge about *evaluation* methods can assist the *selection* of good indicators of condition. Well-chosen indicators can help with future evaluation efforts. Likewise, part of the “problem,” as we estimate it, may be that we initially recognize only a few options as alternatives, and that we need to try creating or identifying more alternatives.

By considering the components of a policy process as part of an interdependent whole, rather than separate steps, both greater understanding and better decisions become more likely. In contrast, focusing on each policy process component as a separate step can reduce our opportunities for understanding and thereby lead to decisions that are based on unnecessarily narrow comprehension, a sort of tyranny of small decisions.

Science Plays a Subordinate Role

If the policy process is a supraorganization and based upon integration, then no single organization or input is more important than the others. Each organization, including the broad organization of scientists, is subordinate to the larger policy process.

We can think about this from another direction, as well. The scientific process—from formulating careful hypotheses to collecting data and analyzing it in a repeatable manner and presenting formal conclusions—centers around necessarily confined questions. Policy processes, in contrast, deal with larger, more immediate concerns, so science is again subordinate to a policy process. Duinker and Beanlands (1986) and Duinker (1989) offer some of the more compelling arguments, expanding upon and explaining this idea quite well.



Science Plays an Important Role

Although science is subordinate to the larger policy process, it certainly has important roles to play within that process. Application of scientific methods can help us better understand situations, anticipate possible consequences of a proposed action, and assess effects of implemented actions. For these reasons, science is central to any effective policy process, especially one that seeks to integrate knowledge about the physical, biological, and social conditions at play (Clark, 1992). Scientific methods are available to identify trends and allow the policy process to incorporate ways of knowing whether conditions are changing, how they are changing, and whether they are changing in an expected manner (Duinker, 1989).

Science Can Help Identify Issues and Concerns, Including Barriers

Another way science and scientists can play an important role within a policy process is by helping identify issues and concerns relevant to current situations (Blahna and Yonts-Shepard, 1990). Scientists who work in physical or biological science disciplines, for example, can document conditions and trends in changing conditions. Similarly, scientists who work in social science disciplines can document concerns of those participating in the policy process or who will likely be affected by its outcome, including concerns that public meetings may not identify. In fact, scientists themselves may have concerns that a successful policy process will have to address, concerns such as the condition of study sites, opportunities for continued or future research, or incorporation of scientific findings into management decisions.

Successful policy processes will recognize and act upon the need to identify potential barriers or obstacles to effective management. Some obstacles can be political, others institutional, and still others logistical. Scientists, especially those working in social science

disciplines, can help identify such barriers, whether real or perceived.

All scientists, however, can gain by reflecting upon how they might be perceived as an obstacle. For example, local residents can resent so-called outsiders or experts arriving and, as the residents might see it, telling them what to do. Similarly, managers might resent scientists who give the impression their answer is correct over all others. Work by Waddell (1990) shows convincingly that scientists who emphasize the logic of their conclusions, with no acknowledgment of their own interests and concerns, are greeted warily. Another way in which scientists can become a barrier is if they act to limit discussion to traditional participants, such as managers, scientists, and other experts, instead of soliciting knowledge from as many constituency sources as possible. Reflecting upon the way we might act as barriers can illuminate ways we can better contribute to policy processes.

Democratization of Expertise

Perhaps the most important implication of this paper's conception of the policy process is that expertise is becoming increasingly democratized. Every participant in the policy process, whether a local resident, agency employee, scientist, or some other stakeholder, has a particular perspective on the situation and understanding of its dimensions. Accordingly, every participant is an expert on that perspective and we can learn from each participant just as they can learn from us (Fischer, 1993; Renn et al., 1993).

One way of thinking about this is that not all participants will describe a situation in the same manner, speak with the same vocabulary, or recognize the same issues, so they offer complementary sets of expertise. Taken together, the varied descriptions, vocabularies, and issues provide a more full understanding of a situation. We gain by thinking of these people as additional sources of knowledge, ideas, and information. By sharing our knowledge and learning from knowledge available through other people, better understanding



will result. For example, some people will say that conditions indicate a problem or problematic trend and other people looking at the same conditions will see conditions as stable or improving. A policy process that seeks to understand why people see things differently is more informed about concerns relevant to the situation.

For scientists, several points are important to consider. One is that social science provides methods for identifying these different perspectives, especially in conjunction with other methods for identifying critical issues and concerns, such as facilitated discussions and traditional meetings. Another important point is that natural science can offer knowledge about conditions and trends that expands upon and complements the understanding of other participants in the policy process. With new information, some people's concerns will change. For scientists, we may formulate additional hypotheses when we learn of other's ideas that we had not considered. Likewise, we may present findings in a way that better addresses concerns of others by selecting language or topics relevant to those concerns.

Case Study of a Policy Process

Until now we have discussed policy processes and key related ideas at a fairly broad, somewhat abstract level. A case study, however, often provides a more concrete example of how these ideas can play out when applied to a real situation, especially if the six phases or components of a policy process, described earlier, serve as a framework for describing the case. Throughout the following case study, I emphasize the role of science and scientists to reinforce earlier points.

First, let me provide some background. In 1994, the National Park Service began an effort to improve and, where possible, better manage wildland resources in Great Smoky Mountains National Park. Their effort

incorporated physical, biological, and social sciences as part of a participatory process. From its inception, the planning process integrated science with management and, in the end, strengthened science's role in administering the Park. The project's initial planning phase ended 1 year later and forms the basis for this case study. Documentation of the case study appears in the management plan entitled *A Strategic Plan for Managing Backcountry Recreation in Great Smoky Mountains National Park* (USDI-NPS, 1995).

Part of understanding a situation involves understanding its setting. Great Smoky Mountains National Park is located in a mountainous area of the southern Appalachians of the eastern United States. There are 515,000 acres within the established boundaries, an area about one-third the size of the new Monument. Annual precipitation in the Park is 80 inches in places, enough to qualify it as a temperate rainforest with sensitive soils and plants. It is a very ecologically diverse area with eight types of forests, 400 rare plant species, and 10 endangered animal species. As significant as any other characteristic is the Park's popularity. It is visited between 8 million and 11 million times a year; the Park's backcountry is visited between 700,000 and 500,000 times a year, often for horse riding, hiking, or camping. The Park's trails and campsites are critical components.

Initiation: Recognizing That a "Problem" or Situation Needs Attention

Policy processes begin within an initiation phase. Stated generally for the purpose of this paper, Park staff members and others first described the Park's "problem" as, "*Horse riding is destroying trails and we have to eliminate it before all the trails are ruined.*" Needless to say, horse-riders saw things differently. Many were, and still are, local residents and some have family ties to areas within the Park's current boundaries that predate its establishment. Still, this initial statement of the problem,



regardless of whether everyone agreed, is helpful because it initiated the policy process.

Estimation: Trying to Understand the Situation and How Different People See It

Once a policy process begins, it is necessary to begin trying to understand the particular situation, work that will continue throughout that policy process. In the Park, it soon became clear that the situation consisted of three elements. One element is the backcountry setting with physical, biological, and recreational *contents* and historical, natural, and inspirational *character*. Efforts to understand the Park's setting, for example, consisted of work by scientists to conduct physical and biological assessments to describe soil conditions, water quality, and nonnative vegetation. That work confirmed concerns raised by other knowledgeable persons; it also showed that some concerns were unsupported by evidence. Social science methods also helped assess the setting by addressing questions related to its character, as perceived by stakeholders and constituents.

Opportunities for enjoying the setting, as with a recreational visit, educational experience, or scientific study, are another element. Social science disciplines are most suited for assessing this element. Work that occurred at the Park as part of this policy process confirmed that conditions mean different things depending upon one's perspective, and that *impact* is a socially defined concept. By integrating social science methods seamlessly with the policy process, just as with physical and biological sciences, the policy process became better informed, as did those participating in the process.

The third element is stewardship—those individuals, activities, and materials necessary to care for the setting and its associated opportunities. A policy process intent on providing sustainable conditions and trends will incorporate the idea of stewardship because care by stewards is essential for sustainable conditions.

At the Park, estimation efforts included identifying individuals and groups who might have a stake in the process and then beginning work to find opportunities that could enable them to act as stewards.

Even while seeking to estimate the situation, it was important to identify and discuss objective boundaries, for such boundaries can keep a policy process from becoming an exercise of political whimsy. For example, part of the estimation phase of the case study involved identifying legislative mandates that provided the broadest direction for selecting stewardship actions. Any action implemented as a result of the policy process had to fit within those mandates. By making discussion of legislative mandates part of the policy process, we ensured that proposed actions stayed within the boundaries of what is legal and appropriate. Effectively, we treated legislative mandates as an objective tool for guiding a process and, simultaneously, a coarse filter to eliminate issues, concerns, and proposals that exceeded those mandates.

An important outcome of the estimation process during this case study was that participants were able to find a more common definition of the problem. Because of the learning that occurred for everyone during this phase, the problem became restated as, "*How do we improve backcountry conditions and maintain decent conditions for the future?*" The problem became a question, as opposed to a statement that inferred both blame and an overly simplistic answer.

Selection: Where Do We Want to Go and What Will Help Us Get There?

During the selection phase of the Park's policy process, scientists also played several important roles. For example, they assisted efforts to build a preferred vision for the backcountry and its management. In doing so, they ensured that the idealized backcountry reflected scientists' concerns and included a clearly enunciated role for science.



Another role scientists played in the selection phase is that they helped identify some of the possible tools for addressing the situation and described how certain proposed actions might alter conditions. In this case, additional ideas for tools and options came from other participants and Park constituents. While considering which tools to select, scientists talked about the importance of evaluation and monitoring as a management tool, further demonstrating how an integrated understanding of the policy process was crucial.

During the selection phase, however, one must remember that even the best scientific information will not eliminate the politics of choosing. Science can inform the process so selected tools and actions are most likely to address issues and concerns in a manner sensitive to the situation. Neither science nor scientists, however, are properly equipped to make those choices alone.

Implementation: Taking Action

At the Park, collaboration among stakeholders and constituents produced a management plan, increased trust for the process, and ensured broad support for its outcome. In this way, the policy process marked by collaboration improved the policy decisions—the content—that continued the process. More specifically, scientists helped integrate *evaluation* concerns into the policy document, ensured that concerns about water quality and nonnative vegetation were represented, and provided support in the form of guidance as joint trail work projects began. Some of the knowledge and information provided by scientists could not have come from any other source. In other cases, scientists offered ideas complementing and reinforcing those coming from other sources.

Evaluation: What Are the Conditions and Are They Moving in a Desired Direction?

Unless evaluation occurs as part of a policy process, there is no way of knowing existing

conditions in an objective and repeatable manner. Neither is there an opportunity to assess whether conditions are changing or not changing. Likewise, there is no way to know whether the selected actions are producing intended results or that change is occurring in an intended direction.

Implicit in all this is a need to state conditions that are desirable, a need easily addressed during a participatory planning effort grounded in a clear understanding of legislative mandates. Although the process of stating the desired conditions is a political process beyond the capacity of science or scientists alone to address, scientists have important roles to play, as described earlier.

In Great Smoky Mountains National Park, the backcountry management policy process included an initial evaluation of conditions. Scientists provided baseline information that helped identify conditions as the policy process began. That information also will assist future efforts to assess conditions and identify trends. In addition, scientists helped ensure that the policy process adopted a feasible and meaningful process for monitoring conditions, even if some finer details of a monitoring program are not yet worked out. Also, scientists helped ensure that existing National Park Service programs to monitor water quality, air quality, nonnative vegetation, and various other indicators of forest health are incorporated into the backcountry management program where appropriate and are identified within the policy document as ongoing, complementary efforts.

Perhaps the greatest assistance provided by scientists in anticipation of the evaluation phase is seen in the document's objectives. The policy document (i.e., the management plan) states management objectives in a manner that is specific, unambiguous, measurable, and time-bounded. With objectives stated this way, scientists can compare the results of future assessments with clearly stated criteria for success and failure, greatly reducing likelihood of subjective or biased conclusions.



Note, however, that scientists did not select those objectives alone; mostly, their role was to propose some objectives for consideration and help express all objectives in a measurable format. Also note that objectives, as applied in this case study, follow from the more generally stated vision for future backcountry conditions, priorities for addressing those conditions, and goals for the setting, opportunities, or stewardship elements. All this is explained most fully in the management plan (USDI-NPS, 1995) and is beyond the scope of this paper.

Termination: Actions Become Unnecessary or New Problems Arise, So Time to Start Again

The actions taken as a result of this policy process in Great Smoky Mountains National Park continue to accomplish what was intended or have not been superseded by new problems, so the termination phase, as with much of the evaluation phase, has not occurred. The Park's policy process is intended to provide a flexible approach to improving and maintaining the social, physical, and biological conditions within the Great Smoky Mountains National Park's backcountry.

Even if changes occur, and they will, the policy process applied during this case study and incorporated as part of the Park's backcountry management policy document is likely flexible enough to respond without going through the work of finding a new approach. In addition, the process appears to have fairly broad support from Park staff members, horse riders, hikers, and other constituents and stakeholders. Such support may mean fewer incentives for finding a wholly new approach to policy. This may well change. A flexible approach, however, is quite capable of adapting to new conditions, issues, and concerns that inevitably arise.

Closing Thoughts: Advantages of Thinking About the Practice of Science Within a Policy Process

This paper has offered a literature review and a case study to make the argument that natural science topics of this symposium fit within the larger context of participatory planning and policy. In the future, science practiced within the new Monument also will occur within this larger context. The case study illustrates that science, reason, and quantification will not eliminate politics. We all know this; yet, the point is still worth our consideration. Our audience—managers, local residents, and the public as a whole—also knows that interests affect reasoning; they know that data, more than just describing events, shapes policy. We need to remember our scientific work occurs within a policy context; we need to see the value in reconsidering our professional norms, in reflecting on the ways we have been taught to think.

The discussion about the role of science within a policy process, together with the case study of the planning process at Great Smoky Mountains National Park, suggests several closing ideas about scientists, managers, and the new Monument. At the Grand Staircase-Escalante National Monument, pursuit of a collaborative and interdisciplinary policy process is likely to lead to better understanding of the interests, issues, and concerns at play. We are more likely to understand the "problem" and the "barriers" to addressing it. From better understanding comes better science.

The case study also shows us that self-criticism can promote scientific progress, perhaps most notable because science is a principal purpose for establishing the new Monument. Scientific progress can often occur when scientists take a critical look at their discipline and its place in society. Thinking about what it means to work



within a policy process and working to ensure the process remains open is often as self-serving as it is altruistic. For scientists, this may mean a greater likelihood that management documents incorporate evaluation concerns, that measurable objectives are clearly established, and that science is better integrated within policy documents and has a clear, substantive role within the ongoing policy process. We can learn more and have more opportunities to share what we know when we are engaged in a policy process. The Grand Staircase-Escalante National Monument provides a tremendous opportunity for scientists to engage in a meaningful policy process.

Scientists have an important role to play as stakeholders within such a policy process. We offer expertise needed to evaluate resource conditions, for example. Yet we, too, are stakeholders: we have an interest and a stake in the process. While our *methods* are objective in the sense they are repeatable by others, *we* are involved participants in a policy process and we are not objective. By entering the new Monument's policy process honestly as stakeholders, other stakeholders are likely to seek scientific expertise, as opposed to distrusting it. Manring's (1995) work and the case study both illustrate this. While science and scientists are subordinate to the policy process, they are also central to an effective, workable, and meaningful policy process.

The understanding of policy processes in this paper offers advantages to scientists. One is that scientists who acknowledge and then embrace this broader context can play a more central role in policy processes that affect us and our work. The case study is an example of this because issues and concerns raised by scientists are reflected in the policy. The new Monument provides a new opportunity to pursue an integrated, multidisciplinary, and participatory approach to policy decisions.

The understanding of policy processes in this paper emphasizes sharing of knowledge. Both the new Monument and scientists who care about it can benefit from shared knowledge. By sharing our knowledge and by learning

from others, the policy process for the new Monument is likely to seek more scientifically grounded information, not less. It is likely to seek decisions based upon the best information available and define success and failure with meaningful, objective, repeatable criteria, each a hallmark of good science.

Whether we realize the potential benefits of this understanding depends upon whether we are willing to give up some of our traditional ideas about knowledge. When a policy process is made open, more knowledge is made available to its participants, a point illustrated by the literature review and case study. At the new Monument, science and scientists are likely to gain the most by not trying to drive the policy process and, instead, joining the process as active participants.

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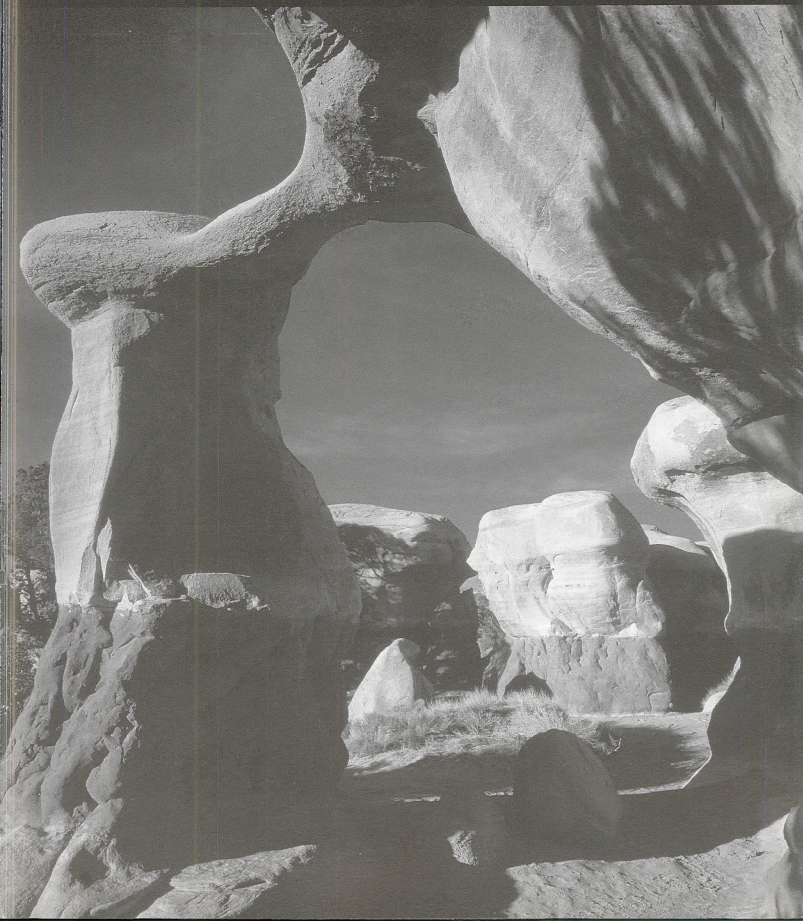
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POSTER SESSIONS







GIS and Multimedia for Rock Art Research, Management, and Interpretation at the Grand Staircase-Escalante National Monument

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ABSTRACT

■ A comprehensive GIS/image rock art database is essential for both research and resource management. The Grand Staircase-Escalante National Monument (GSENM) has unique and fragile cultural resources that have the potential to answer research questions not answerable elsewhere. The border between the Anasazi and Fremont people lies almost entirely within the region now covered by the GSENM. Researchers debate whether the two cultures form clearly separate societies, or merely represent ends of a social continuum (Madsen, 1997). By mapping differing rock art styles, adding to the data by Castleton and Madsen (1981) and Tokioka (1992), and analyzing that data along with other relevant data layers, questions about the interactions between these cultures, their patterns of movement, and ancient land use may be answerable (Geib, 1996).

Archaeological sites need to be inventoried before multitudes of visitors come and disturb or vandalize them. Already some rock art sites within the GSENM are heavily visited and are suffering vandalism and other impacts. A GIS database will be a necessary component of a monitoring and management system. It should contain accurate site location and condition information that will help managers make decisions on areas to develop, interpret, or restrict.

The same data resources will also facilitate the development of interactive, multimedia interpretive materials for visitors, Web pages, and CD's. Carefully designed interpretive materials can be used to control impacts and encourage visitation at selected sites. Technology such as QuickTime Virtual Reality panoramas with imbedded hotspots that connect with closeup images can be applied. Also, images can be incorporated into traditional GIS data layers, adding an important visual dimension to the research potential at the GSENM.



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Soil Properties Influence the Distribution of Jones *Cycladenia* (*Cycladenia Humilis* Var. *Jonesii*), A Rare Endemic Plant of the Colorado Plateau

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ABSTRACT

■ Jones *cycladenia*, *Cycladenia humilis* var. *jonesii* (Eastw.) Welsh and Atwood (Apocynaceae), a Federally listed threatened taxon, occurs in soils developed from shale in three geologic formations of the Colorado Plateau in southern Utah and northern Arizona. Jones *cycladenia* (CHJ) was an assumed obligate gypsophile (Welsh et al., 1987) and possible indicator of selenium (Se), uranium (U), or other trace elements.

Morphological and chemical properties were compared between soils supporting four populations of CHJ and adjacent soils that do not support CHJ. At least three soils were investigated in each of four areas that support CHJ (San Rafael Reef, Castle Valley, Onion Creek, and Deer Point, which is located within the Grand Staircase-Escalante National Monument). At least two soils in adjacent areas that do not support CHJ were also investigated. Soil morphological properties were described in detail. Genetic soil horizons were sampled and analyzed in the laboratory.

Because rock fragment content was typically high in subsoil horizons (90 to 100 percent by volume), whole soil was analyzed instead of fine earth fraction (<2-mm fraction). Whole soil samples and rocks were air-dried and crushed gently in a ceramic mortar and pestle to pass through a brass sieve with a 4-mm opening. Organic carbon (C) was determined on triplicate soil samples using a sulfuric acid-potassium dichromate digestion and titration (Nelson and Sommers, 1982). Available phosphorus (P) was extracted using the sodium bicarbonate method (Olsen and Sommers, 1982) and measured colorimetrically. Total nitrogen (N) was measured by Kjeldahl digestion and titration (Bremner and Mulvaney, 1982).

Whole soil material and rocks crushed to <4 mm were equilibrated with distilled/deionized water to simulate the chemistry of the soil solutions. Equal parts (by weight) of crushed material and water were mixed in a centrifuge bottle and allowed to equilibrate for \$100 hours, with daily gentle agitation. Soil-water suspensions were centrifuged and the supernatant vacuum filtered



through a 0.47- μ m filter, then through a 0.2- μ m filter. The pH and electrical conductivity (EC) of the extracts were determined. Composition of extracts were determined using inductively coupled plasma spectroscopy (ICP). The ICP results were checked for accuracy against standards provided by the Environmental Protection Agency.

Aluminum (Al), gold (Au), boron (B), barium (Ba), calcium (Ca), cobalt (Co), chromium (Cr), iron (Fe), potassium (K), lanthanum (La), magnesium (Mg), sodium (Na), nickel (Ni), phosphorus (P), strontium (Sr), thorium (Th), titanium (Ti), uranium (U), vanadium (V), tungsten (W), and zinc (Zn) of soil material were determined by aqua regia digestion (Lim and Jackson, 1982) and analysis by ICP. Silver (Ag), arsenic (As), bismuth (Bi), cadmium (Cd), copper (Cu), gallium (Ga), molybdenum (Mo), lead (Pb), antimony (Sb), selenium (Se), tellurium (Te), thallium (Tl) were determined by organic solution extraction and ultrasonic ICP. Mercury (Hg) was determined by cold vapor atomic absorption spectroscopy (AA). Trace element analyses were performed by Acme Analytical Laboratories, Vancouver, BC.

We found that CHJ is not an obligate gypsophile; soils from only two populations contained gypsum, based on the solution chemistry results. The concentrations of Se and U in all soils were less than or equal to detection limits and less than or equal to the worldwide average concentrations for shale (Krauskopf, 1979). Soils were moderately high in heavy metals, but variability among soils supporting CHJ was as high as variability between soils supporting and not supporting CHJ.

Instead of having a restricted range of soil chemical properties, CHJ appears to be restricted to soils with a very narrow range of morphological and physical properties. Soils are shallow (<50 cm), have high rock fragment content (increases to almost 100 percent with depth), and is formed in shale that fractures angularly in situ. Although soils that support CHJ often occur on steep slopes (≤ 50 percent) with erosive surfaces, deeper horizons are stable. The ramets of CHJ anchor and proliferate in horizons composed of fractured shale overlying the rock contact. The proliferation of CHJ roots in the soil horizon just above the rock contact is reflected by relatively high organic C, total N, and available P concentrations in this horizon.

Our previous studies of reproductive biology and genetic structure indicate that CHJ has very low potential for sexual reproduction and relies primarily on clonal growth (Sipes and Wolf, 1997); thus, establishment of new populations by seed is unlikely. Because the physical and morphological soil requirements of CHJ would be difficult to meet outside its natural environment, "captive breeding" management programs are infeasible. Conservation efforts should focus on protecting existing populations and minimizing habitat degradation.

Because the Colorado Plateau of southern Utah supports large numbers of endemic species, reasons for endemism must be elucidated and incorporated into management plans. Information about soil properties can be useful in

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interpreting vegetation patterns and can help managers plan appropriate land use and management practices.





Hydrogeology and Water Resources of the Grand Staircase-Escalante National Monument

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ABSTRACT

■ The Grand Staircase-Escalante National Monument includes exposed geologic formations that range from Quaternary-age alluvium to Permian-age limestone and shale and represent a timespan of more than 230 million years. These formations were deposited and subsequently sculpted into the forms we see today, largely by the forces of surface and subsurface water. The area receives only about 7 to 18 inches of precipitation annually, a typical arid to semiarid environment. Wise management of the Monument must include managing the many needs for this water to assure that existing life and hydrologic processes within the Monument are sustained at the present level or one that is acceptable to the Monument's caretakers.

There are several aquifer systems underlying the Monument. The main aquifer system is within the Navajo Sandstone and underlying sandstones that exist in most parts of the Monument. This system is part of a regional system that encompasses parts of Colorado, Arizona, and Utah and is now called the Glen Canyon aquifer. This aquifer is recharged partly by precipitation that infiltrates the Navajo Sandstone where it crops out in the northeastern and southwestern parts of the Monument, and partly by snowmelt and rainfall that infiltrate the higher plateaus to the north and the Kaiparowits Plateau, where the water must move down through overlying strata before it reaches the Glen Canyon aquifer. The Glen Canyon aquifer sustains part of the base flow in Johnson Creek, the Paria River, and the Escalante River and its tributaries.

Other regional aquifers exist under the Monument. The Kaiparowits Plateau includes the Mesaverde, Dakota, Morrison, and Entrada-Preuss aquifers that overlie the Glen Canyon aquifer. Carbonate aquifers of Paleozoic age underlie all of the Monument, but are largely inaccessible because of depth. Direction of ground-water movement, estimated from water levels from a few wells and from knowledge about the nature of recharge to aquifers, is from the northwest to the southeast, toward Lake Powell. From meager data sites it is thought that, locally, ground water moves toward and discharges into the deepest canyons. Thickness of the regional aquifers in Mesozoic-age rocks ranges from 200 feet for the Dakota aquifer to 2,200 feet for the Glen Canyon aquifer.

The quality of the surface and ground water of the Monument is important to the type of ecosystems that can be supported and to how these ecosystems



need to be managed. Existing water samples indicate that the dissolved mineral content in ground water of the Monument ranges from generally less than 1,000 milligrams per liter where the Glen Canyon aquifer is exposed, to as much as 10,000 milligrams per liter in selected aquifers and locations under the Kaiparowits Plateau. Surface water contains generally less than 1,000 milligrams per liter dissolved solids throughout the Monument, except in selected streams draining to the south on the Kaiparowits Plateau.

Hydrologic data available for the Monument could be updated and augmented to provide managers the coverage they need to make decisions about the future of the Monument. Only one streamgage, Pine Creek, is currently being operated within the Monument, but a real-time site is operated on the Escalante River near Escalante. Discharge data for 16 historic sites are available. There are historic water-level data and field water-quality data for about 125 wells or springs collected in the early 1980's. Current data are being collected at only two of these sites. More comprehensive laboratory analyses were performed on samples from 63 of these sites.

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Uncharismatic Microfauna of the Colorado Plateau: Notes on Distribution and Ecology of an Undescribed, Pothole-Dwelling Ameronothroid (Acari: Ameronothridae) Mite

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Potholes are small basins in bedrock that collect precipitation, forming ephemeral aquatic habitats. They are relatively harsh environments for aquatic organisms, especially when dry.

Potholes range in size from tiny depressions holding less than a liter of water to huge pools, up to 18 m deep and over 20 m across

ABSTRACT

■ Potholes, or rock pools, are common in exposed sandstone on the Colorado Plateau and support a diverse array of aquatic invertebrates. An undescribed species of ameronothroid oribatid mite resides in very small potholes (pans), holding only a few liters of water. This mite has been placed in the genus *Aquanothrus* (Acari: Ameronothridae), which contains only one other species (*A. montanus*), found in ephemeral rock pools in South Africa. *Aquanothrus* n. sp. occupies pans that are extremely short-lived, yet months may pass between rains. It is apparently not cryptobiotic in that it does not tolerate desiccation of its tissues. Morphological characteristics and observations of length of survivability indicate instead that it resists desiccation. While not tested quantitatively, few mites appear able to survive more than a year when stored dry.

This mite has been found across much of the central portion of the Colorado Plateau on sandstone exposures of Permian to Cretaceous age. It is limited to areas where small weathering pits form in the rock, but it is apparently absent from many areas that seem suitable, including many sites that have been examined in the Grand Staircase-Escalante National Monument. It is not clear what makes a pan suitable or unsuitable for mites. We suspect a combination of physical factors and biotic interactions are involved. This mite is a very unusual organism, of interest from evolutionary, physiological, and morphological, as well as biogeographic perspectives. As such, it deserves protection. Further investigations into its ecology are needed if it is to be protected in the Monument and elsewhere on the Colorado Plateau.

(Netoff et al., 1995). Different organisms may occur in pools of different sizes as a result of interactions between life cycle length and pool



longevity (Dodson, 1987), although other factors also play a role in determining pothole community composition.

One of us (TBG) found small mites (Figure 1) in very small potholes in 1988. It is a new species of oribatid mite in the genus *Aquanothrus*, which was erected by Engelbrecht (1975) for the species *Aquanothrus montanus* discovered in ephemeral pools in South Africa. The Colorado Plateau mite represents only the second species in the genus *Aquanothrus*.

Both *Aquanothrus* species are found in ephemeral rock pool microhabitats. They have

been found only on midelevation plateaus in semiarid to arid climates, living in weathering pits formed in late Paleozoic to late Mesozoic sandstones. They have a secondary light receptive organ, called a lenticulus, that resembles the lenticulus of the Hydrozetidae, a common aquatic mite family (Alberti and Fernandez, 1990). Both species of *Aquanothrus* have unusual leg trachea as well (Norton et al., 1997). Herein we discuss the distribution and what little is known about the ecology of the Colorado Plateau species of *Aquanothrus*.

Materials and Methods

Distribution

No systematic surveys have been conducted to determine the distribution of this mite. Rock pools on and near the Colorado Plateau have been examined by the authors during travel; in some cases, looking for mites has been a major function of taking a particular route across the Colorado Plateau. Rock outcrops with exposed relatively horizontal surfaces were examined wherever encountered on the Colorado Plateau; if boulders had depressions that showed evidence of holding water at times (black bathtub ring) and sediment, they were also examined. A small sample of sediment was scooped up with a spoon and wetted to activate mites. Thus far, no attempt has been made to assess habitat quality across the Colorado Plateau by comparing mite populations in different kinds of pools.

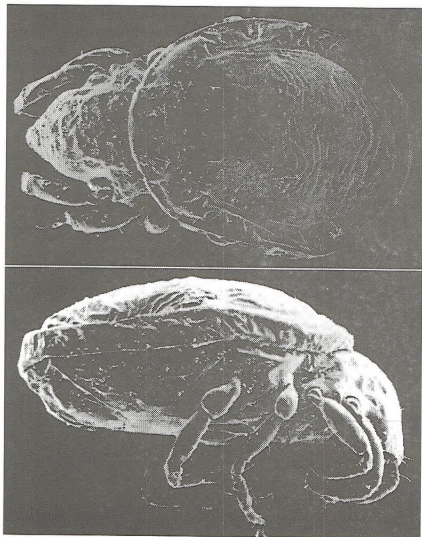


Figure 1. Dorsal and lateral views of an undescribed mite, near *Aquanothrus*, inhabiting very short-lived rock pools on the Colorado Plateau. The mite is approximately 0.77 mm long, the widest part of the abdomen is about 0.38 mm, and the body is roughly 0.15 mm thick. (Scanning electron micrographs by John Gardner, Brigham Young University, Provo, UT.)



Habitat Requirements

Over 60 pools have been characterized near Moab, Utah where the mite was first discovered. Each pool was measured and examined for mites and other organisms. Length, width, and depth were measured, and surface area and volume were estimated. Maximum sediment depth was also measured. Pool sediment was examined for the presence of mites, rotifers, and gnat larvae, and the sediment surface assessed for the degree of cyanobacterial crust development. These data were analyzed using principal components analysis to look for pool characters that may correlate with mite presence or absence.

Results and Discussion

Distribution

The known distribution of this mite is shown in Figure 2. The x's represent locations where mites are present; the dots are locations where pools were examined, but no mites were found. The vast areas with no marks indicate areas that have not been surveyed, and include unsuitable habitat (e.g., most Mancos Shale exposures). We have examined few sites outside Utah; this is a reflection of our travel patterns rather than mite distribution.

Mites have been found across much of the central Colorado Plateau, from 1,060 m to 1,980 m above sea level on sandstones of Permian to Cretaceous age (Figure 2). Only cursory surveys have been made across most of the southern Colorado Plateau (Figure 2), and no work has been done in the northern portion of the Colorado Plateau.

Most mite pools are in fine-grained sandstones such as Navajo and Wingate Sandstones, and coarse-grained sandstone deposits such as the Cedar Mesa, White Rim, and Dakota Sandstones. Some Entrada exposures (e.g., the Moab and Slickrock Members in Arches National Park) also contain many mite pools; however, the mite appears to be absent on Entrada outcrops in the Escalante and Capitol

Reef region. The Entrada is comprised of finer sediments and is softer in central and western Utah than eastern Utah (Baars, 1983). This may play a role in suitability for mites. Mites have not been found in other soft sandstones or siltstones (e.g., Morrison and Moenkopi Formations). More work is needed to determine the full distribution of this mite. Most of the Colorado Plateau has not been adequately surveyed, but even where we have surveyed, it is missing from pools that appear to be suitable.

A combination of biotic and physical interactions probably determine geographic and elevational distribution of this mite. At lower elevations and latitudes, a small pool may not last long enough for mites to replace the energy used in generating and breaking dormancy, but larger pools may support mite predators. At high elevations and latitudes, mites may not have enough time where they are both wet and warm enough for efficient metabolic activity to acquire sufficient energy to successfully reproduce.

Habitat Requirements

Lower pan size limit is predicted to be determined by the minimum amount of time needed to acquire the energy necessary to reactivate metabolic activity following rehydration plus the energy required to resist dehydration again. There could be a minimum amount of sediment needed as well. Sediment may provide protection for mites from wind, and perhaps from exposure to ultra-violet radiation or other stressors. Upper limit on pan size is probably based on biotic interactions, especially predation. Mites move across sand surfaces clumsily, and are probably easy prey for active predators such as gnat larvae and tadpole shrimp.

The attempt to characterize physical parameters of small pools to look for either positive or negative correlations with mite presence has not been very successful to date. A total of 61 pools were described; 42 contained mites, 19 did not. Mites were found in pools throughout the full range of each parameter (Table 1), and there is complete overlap between pools with mites and pools without mites. Principal component analysis indicates

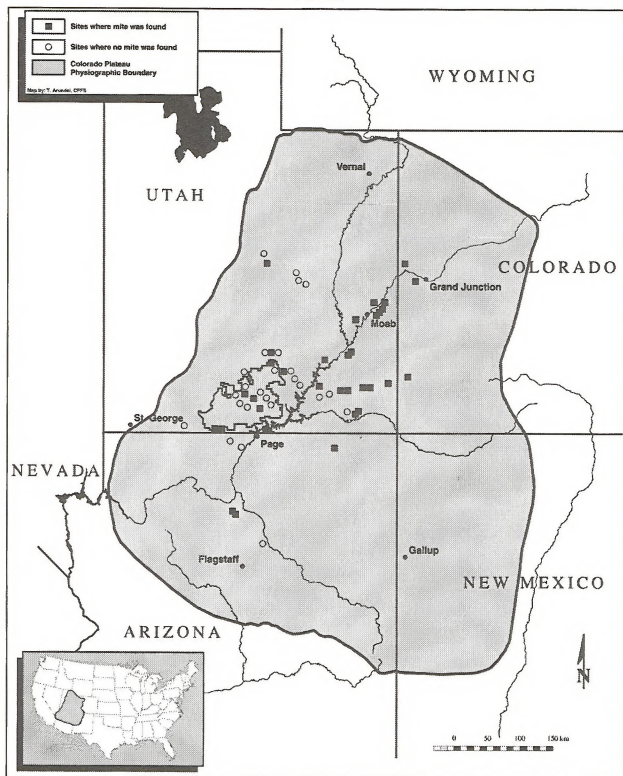


Figure 2. Schematic map showing the Colorado Plateau boundary, major rivers of the Colorado Plateau, and State boundaries. The squares indicate locations where the mite has been found; the circles represent locations that were surveyed for mites, but no mites were found.



Table 1. Ranges for pool characteristics measured in 61 pans in Navajo Sandstone near Moab, Utah. Mites occurred in 42 pans and were absent from 19 pans.

Pool parameter	Pools with mites	Pools without mites
Depth	0.5-10.0 cm	0.65-5.7 cm
Surface area	23.8-24,053 cm ²	50.3-11,216 cm ²
Volume	0.108-40.75 L	0.075-63.9 L
Sediment depth	0.05-7.0 cm	0.01-10.0 cm
Dist. to nearest pool	0.1-4.6 m	0.16-2.86 m
Dist. to nearest pool w/ mites	0.1-9.9 m	0.18-7.0 m

that pool surface area accounts for essentially all of the variability among the pools surveyed, but there was no pattern of mite presence/absence correlated with surface area (Figure 3).

Sediment depth was expected to be correlated with mite presence, since mites retreat into the sediment as pools dry out. They had not been observed on dry rock surfaces exposed to air. But sediment depth was not correlated with mite presence, and a pool with sediment depth of only 0.5 mm had mites.

Surveys appeared to reveal a trend for pools with well-developed cyanobacterial crusts to

be without mites more often than similar-sized pools without a well-developed crust. But at least for the 61 pools surveyed, there is no clear pattern: 23 pools had crust, 38 pools were without crust, 4 of the 19 pools without mites had well-developed crusts, and almost half the pools with mites contained crusts.

Ecology

Aquanothrus sp. is an unusual oribatid mite. Few oribatids are aquatic, nor able to live in the small ephemeral environments these mites occupy. Most oribatid mites feed on fungi and organic detritus. This mite is a predator, feeding on rotifers, although it may also eat diatoms, algae, and detritus. Oribatid eggs are generally unpigmented; this mite's eggs are a bright orange, the same color as the rotifers the mites eat. We don't know if there is a relation between rotifer color and egg pigmentation. Pans can hold surprisingly large mite populations. Over 200 individuals have been counted in pans estimated to contain only 1 L of water.

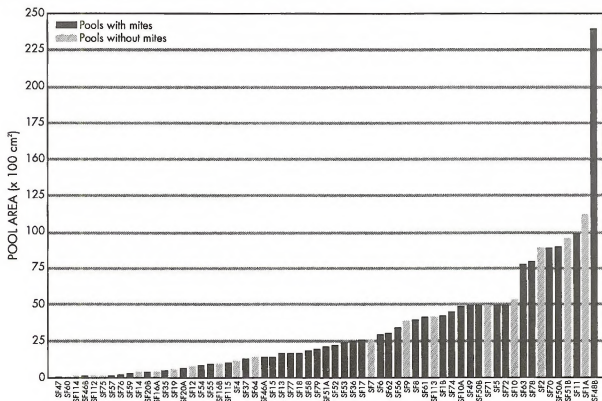


Figure 3. Potential mite pools measured and surveyed in July 1997, sorted by surface area, showing mite pools and pools without mites.



No experimental work has been done on these mites to determine how they survive extended dry periods. They probably do not tolerate desiccation (anhydrobiosis); we suspect they avoid desiccation rather than tolerating water loss. Part of the suite of adaptations that allows them to survive in dry pans may be the unique structure of their cuticle, which is thin but very tight, with little lamination detectable. Their waxy coating is a thin continuous cerotegument, with air-filled chambers connecting to the surface (Norton et al., 1997). The mites are not capable of surviving very long periods without water; samples kept dry over a year rarely contain any live mites (T.B. Graham pers. obs.).

Bright orange patches (up to 30-mm diameter) have been observed in the sediment of some pans, notably those without mites. Examination of these patches revealed they were comprised of thousands of rotifers. These rotifers are present in pans with mites, but at much lower densities. The mite population of one pan was accidentally destroyed in August 1989 and had not been recolonized by October 1993, but the rotifer population became quite dense during that period (T.B. Graham, pers. obs.). Mites did not disperse from the nearest pool with mites (0.61 m) for 7 years (T.B. Graham, pers. obs.). These observations led to the hypothesis that the mites feed on rotifers, and may play a role in rotifer population control. Observations in the lab indicate the mites do indeed feed on rotifers, and can eat all the rotifers in a container in a few days. We have not quantified their impact on rotifer populations in pans yet.

Mites live in shallow depressions rarely recognized as living ecosystems. The mites are limited by availability of suitable habitat of course, but are also impacted by trampling by livestock, vehicles, and other human activities. Near Moab, mites are abundant in areas with little human use over the past 20 years. One area has been used for grazing, off-highway vehicle use, and firewood collecting for many years. I have not seen any mites in hundreds of pans examined here, but many have large

rotifer populations. This may be a reflection of greater human use in this area.

Recreational activity is increasing on the Colorado Plateau, and many areas are receiving very intense use. Human use of some areas currently occupied by mites has increased exponentially over the past decade. Land managers have traditionally encouraged use of slickrock areas to protect the fragile soil and plant communities on the Colorado Plateau. There are few potential indicators on slickrock to monitor recreational pressure. Mite populations may be a useful indicator for this purpose. Comprehensive surveys are needed to document baseline mite populations, and protocols should be developed to monitor impacts as use increases on the Colorado Plateau, including within the Grand Staircase-Escalante National Monument.

These mites are important from a scientific perspective and deserve protection. The disjunct distribution of the genus *Aquamothus* is intriguing, and may provide valuable insights on dispersal mechanisms and biogeography. They can contribute information on evolutionary ecology, the morphology and physiology of desiccation resistance, and other ecological and evolutionary questions. Research into anhydrobiosis of rotifers and tardigrades has led to a number of applications, particularly in processing and storing biological tissues and other substances (Crowe and Crowe, 1990; Crowe et al., 1987). The mites seem to have solved the problems of surviving in a dry environment differently, and they may hold alternative answers to problems of tissue storage and maintenance of molecular structure.

We hear a lot about the charismatic megafauna, and know the emotional and political power members of this elite club wield. *Aquamothus* mites are not cuddly, cute, or fuzzy (Figure 1). They are tiny, inconspicuous, and have twice as many legs as the organisms most people envision when they hear the word animal. They still deserve protection. Please tread lightly on the rocks of the Colorado Plateau and stay out of even the smallest depressions in the rock.



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Geologic Hazards of the Grand Staircase-Escalante National Monument

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ABSTRACT

■ A knowledge of the type and distribution of geologic hazards in the Grand Staircase-Escalante National Monument is an important step in land use planning in the Monument, and is especially crucial in the beginning stages of such planning. Geologic hazards in the Monument include earthquake ground shaking, landslides, rock falls, problem soils, stream flooding, and radon. Knowing these hazards and taking steps to either avoid or reduce exposure to them can help prevent damage and threats to life.

To help make Utah a safer place to live, the Utah Geological Survey, during the 1980's and 1990's, compiled a series of statewide geologic hazard maps to show where geologic hazards are present. A map of the Monument area was derived from these statewide maps (copies are available from the Utah Geological Survey). However, because of its small scale, it should not be used alone in the final assessment of an area's suitability for a proposed land use.

Although no Quaternary faults are identified in the Monument, several faults or fault systems are nearby. These include the Sevier fault just west of the Monument, which may have experienced movement in the late Pleistocene; the Bright Angel fault system east of the Monument; and the numerous faults on the Aquarius and Awapa Plateaus north of the Monument. These latter two systems are believed to have experienced movement during Quaternary time. Earthquakes associated with these faults could generate strong ground shaking inside the Monument and trigger other geologic hazards (for example, flooding, rock falls, landslides).

Landslides and rock falls are common in the Monument. Rock falls occur frequently in Utah, especially where bedrock is exposed in a cliff face or on a slope. Landslides in the Monument are primarily associated with slope-forming geologic formations that are shale- or clay-rich and inherently weak. These formations include the Triassic Chinle Formation, the Jurassic Carmel and Morrison Formations, and the Cretaceous Tropic Shale and Mancos Shale. Landslides are concentrated in five main areas within the Monument: 1) the southeast-facing slopes of the Pink Cliffs (Carmel Fm., Tropic Shale), 2) the southeast-facing slopes of the Vermilion Cliffs (Chinle Fm.), 3) the northeast-facing Straight Cliffs that form Fifty-mile Mountain (Mancos Shale, Morrison Fm.), 4) the Circle Cliffs area that frames the Escalante River in the northeast part of the Monument (Chinle Fm.), and 5) the middle, but predominantly



southern, Kaiparowits Plateau in the southeast part of the Monument (Mancos Shale, Morrison Fm.).

Problem soils in the Monument include active sand dunes, limestone karst, and the most prevalent problem-soil type, expansive soils. Expansive soils create problems when structures or soil-absorption fields are placed in or on clay-rich soil that is prone to shrinking and swelling with changes in water content. Many of the areas having heavy concentrations of landslides also coincide with areas of expansive soils. This is because clays in many of the geologic formations that produce landslides are also expansive.

Stream flooding is a frequently occurring hazard that is common in southern Utah, including in the Monument. Areas subject to flooding are not shown due to map scale, but are generally restricted to stream channels and washes. The most damaging and dangerous form of stream flooding is flash flooding, which can occur when high-intensity thunderstorms pour precipitation over a region having a generally sparse vegetal cover. Rainfall cannot fully infiltrate the ground and stream channels fill quickly, presenting a life-safety risk to humans and animals and causing accelerated erosion.

Radon is a naturally occurring radioactive gas formed by the decay of uranium, which is a common element in rocks of southern Utah. Inhaled radon is associated with lung cancer. On the basis of the distribution of uranium-enriched rocks and other factors that enhance or impede radon movement in the ground, most of the Monument has a moderate radon-hazard potential. The map shows areas having a high radon-hazard potential; these areas are mainly in the southern Kaiparowits Plateau.



Summary of Geologic Investigations Conducted by the U.S. Geological Survey in the Region of the Kaiparowits Plateau, Grand Staircase-Escalante National Monument, Utah

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ABSTRACT

■ During the past 35 years, the U.S. Geological Survey (USGS) has conducted extensive geologic research throughout the 1,650-square-mile area known as the Kaiparowits Plateau, which is located in the Grand Staircase-Escalante National Monument, Utah. These studies have resulted in numerous publications that describe the geology, resources, and deposition of strata within the Plateau and have provided essential data for land use planning and resource evaluation.

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Preliminary investigations of the distribution and resources of coal in the Kaiparowits Plateau, southern Utah. U.S. Geological Survey Open-File Report 96-539. 72 pp.

The USGS initiated its investigations in the 1960's to evaluate the geology and coal resources on Federal lands, which cover about 90 percent of the Plateau. Initial stratigraphic studies provided formal divisions for Upper Cretaceous and Tertiary rocks and a framework for geologic mapping. As a result, the geology of the Kaiparowits Plateau was mapped in twenty-five 7.5-minute quadrangles and published at a scale of 1:24,000. Additionally, the USGS published a series of 1:125,000-scale maps that addressed geologic factors that may affect coal mining within the Plateau. These maps showed drainage patterns, streamflow data, water quality, ground-water availability, scenic features, landforms, surficial and bedrock geology, geologic cross sections, total coal thickness, and overburden.

More recent research by the USGS has provided sequence stratigraphic models that relate the accumulation and distribution of coal-bearing continental and shoreface strata to sea-level fluctuations. These studies have been integrated with data from company drill holes and published geologic maps to determine the distribution and resources of coal that underlie the Plateau's interior regions. Digital maps and databases from these studies model the structure,



overburden, and distribution of total coal, as well as the distribution of coal within various bed-thickness categories. Coal correlations have been made within the established sequence stratigraphic framework and are shown in cross sections. These data have been used by Hettinger et al. (1996) to report coal resources within a variety of geologic and geographic parameters and provide scientific information that addresses issues associated with the Grand Staircase-Escalante National Monument.



Tectonic and Eustatic Controls on Cyclical Fluvial Patterns, Upper Cretaceous Strata of the Kaiparowits Basin, Utah

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ABSTRACT

■ Middle Coniacian through Campanian strata of the Kaiparowits Basin record the migration of the foredeep basin axis as the Sevier thrust belt approached from the west. Three sequences were produced, each consisting of four parts that represent distinct styles of alluvial architecture and together make up a nearly 2-km-thick succession dominated by fluvial deposition. At the base of each sequence are laterally restricted sandstone sheets that grade both laterally and vertically into fine-grained deposits. Next are thick intervals of predominantly fine-grained material containing scattered lenses and thin sheets of sandstone. These intervals grade upward into extensive multistoried sandstone sheets that include very little fine-grained material. Sequences are capped by laterally extensive multistory sheets of gravelly sandstone and sandy conglomerate. Architectural models have been constructed for the John Henry and Drip Tank Members of the Straight Cliffs Formation and for the Wahweap, Kaiparowits, and Canaan Peak Formations to study the effects of eustasy, basin subsidence, and source area tectonics on the evolution of fluvial systems.

Tectonics and eustasy have combined to produce a thick succession of mostly fluvial strata in Upper Cretaceous deposits of the northern Kaiparowits Basin (Figures 1 and 2). Detailed measured sections through the John Henry and Drip Tank Members of the Straight Cliffs Formation, the Wahweap Formation, and the Kaiparowits Formation, together with published reports for the Dakota Formation, Tropic Shale, Tibbet Canyon and Smoky Hollow Members of the Straight Cliffs Formation, and the Canaan Peak Formation, reveal a succession of mostly conformable fluvial strata that is over 2-km thick and deposited in well-defined cycles that are clearly distinguished on the basis of alluvial architecture (Figure 3).

Each cycle is composed of four parts reflecting predictable changes in fluvial style associated with distinct

basin-filling episodes (Figure 4). The entire succession records a transition from combined eustatic and tectonic influences in the basal two cycles to solely tectonic influence for the upper two cycles that is related to the eastward migration of the Sevier thrust belt and adjacent foredeep basin.

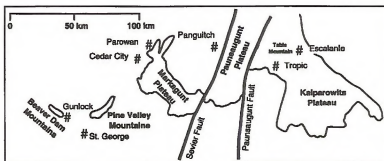


Figure 1. Index map showing the location of major Upper Cretaceous outcrops in southwestern and south-central Utah.

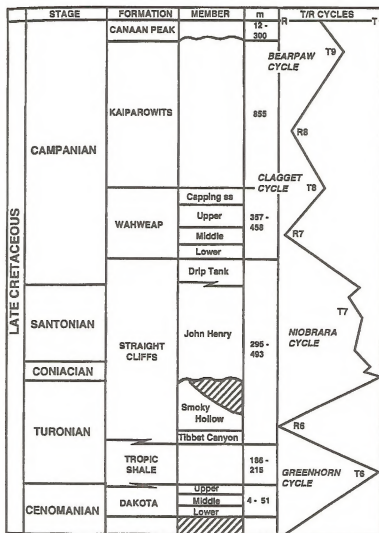


Figure 2. Stratigraphy and ages of Cretaceous rocks of the Kaiparowits Plateau and correlation to recognized Western Interior transgressive/regressive cycles (modified from Bobb, 1991).

The presence of the same four basic parts in each cycle, whether or not eustatic influences are present, strongly argues for a primary tectonic control in proximal foredeep stratal patterns of the Kaiparowits Basin. Each cycle is believed to have begun with the onset of active tectonism in the Sevier thrust belt, which led to rapid basin subsidence and the development of highly aggradational fluvial systems dominated by thick intervals of fine-grained sediment. As tectonism decreased, so did rates of basin subsidence, allowing the basin to fill and producing an upward-coarsening sequence of fluvial deposits. Each sequence is capped abruptly by a coarse-grained sheet associated with much slower subsidence rates during times of tectonic quiescence. Eustatic

effects can be quite significant, but are restricted to more distal portions of the foredeep basin and are therefore expressed only in the lower two sequences. As the thrust belt migrated closer to the location of the Kaiparowits Basin, the relative impact of eustatic processes diminished and the overall succession shows an upward transition from more distal to more proximal deposits.

General Nature of Sequences

Each sequence consists of a coarsening-upward succession of fluvial strata divisible into four parts on the basis of alluvial architecture (Figure 4). The boundary between sequences is marked by an abrupt vertical shift from thick, laterally extensive multistoried sheets dominated by gravely sandstone and sandy conglomerate below to relatively thin, laterally restricted sheets of fine-grained sandstone interbedded with equally thick intervals of mudstone and siltstone above. The boundary between sequences is sharp, but conformable.

Scouring equal to the thickness of a single channel deposit or less is typically present and is believed to be the result of normal fluvial processes and not due to entrenchment associated with a significant lowering of base level.

The basal part of each sequence is made up of one or more laterally restricted sandstone sheets. These sheets may or may not show overlapping relationships and consist primarily of trough cross-bedded, fine- to medium-grained sandstone at the bottom, grading upward to fine- or very fine-grained wavy and parallel laminated sandstone at the top. Interbedded mudstones are sandy and silty at their base and contain scattered thin sandstones throughout. These thin sandstones pinch out laterally over

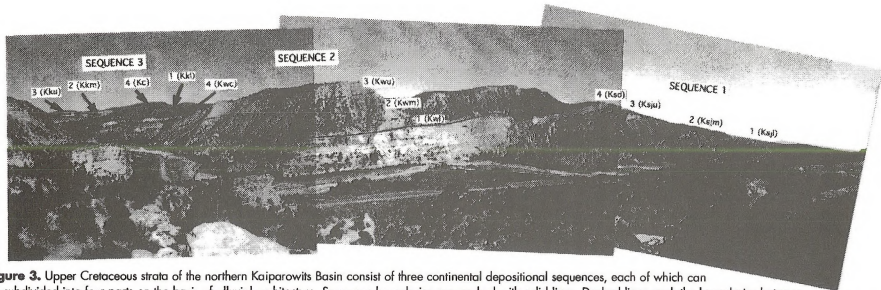


Figure 3. Upper Cretaceous strata of the northern Kaiparowits Basin consist of three continental depositional sequences, each of which can be subdivided into four parts on the basis of alluvial architecture. Sequence boundaries are marked with solid lines. Dashed lines mark the boundaries between the parts of a sequence. Ksj, Ksjm, and Ksju refer to the lower, middle, and upper parts of the John Henry Member. Ksd shows the Drip Tank Member. Kwl, Kwm, Kwu, and Kwc mark the lower, middle, upper, and capping sandstone members of the Wahweap Formation. The lower, middle and upper parts of the Kaiparowits Formation are indicated by Kkl, Kkm, and Kku. Kc shows the location of the Canaan Peak Formation. Numbers 1 through 4 indicate the relative position of the unit within the sequence. The general characteristics of these sequences are shown in Figure 4.

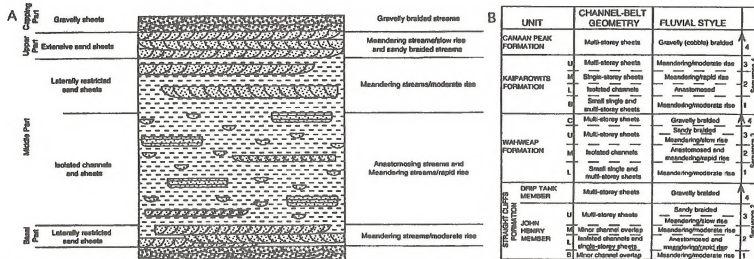


Figure 4. General nature of fluvial sequences in the northern Kaiparowits Basin. Each sequence is divided into a basal, middle, upper, and capping part as shown in A. These are numbered 1 through 4 respectively in B. The letters along the right side of the unit column in B refer to the stratigraphic position within that formation or member. B = basal, L = lower, M = middle, U = upper, and C = capping. Sequence 1 consists of the Dakota Formation, Tropic Shale, and Tippet Canyon and Smoky Hollow Members of the Straight Cliffs Formation. These units were not studied as part of this project and have not been included in this figure.



relatively short distances. The entire unit rests sharply, but conformably, on a planar surface capping the underlying sequence. These deposits are interpreted as having been formed within meandering stream systems under conditions of slow to moderate rates of accommodation space production. The John Henry Member, at the base of the upper Straight Cliffs sequence, contains considerable evidence of marine influence, including brackish water fossils and features suggestive of tidal processes (Shanley, 1991; Shanley and McCabe, 1991).

The middle part of each sequence is made up of laterally discontinuous ribbon or single-story sheet sandstones entirely encased in mudstone. Sandstones typically are trough cross-bedded at the bottom, becoming more wavy or parallel laminated toward the top. In some sheetlike bodies lateral accretion surfaces have been identified. Narrow, multistory sandstones generally do not contain evidence of lateral accretion, except for scroll bars on the upper surface of the capping story. Contacts between sandstones and underlying mudstones are sharp and erosional. Rounded mud clasts a few millimeters to several centimeters in diameter are common near the base of these sandstones, and larger, generally elongate, mud clasts up to several decimeters long occur near the base of some units. Gastropods, bivalves, bone fragments, and turtle shell fragments may be locally abundant at the base of these units. Upper contacts between sandstones and encasing mudstones are typically sharp, but conformable. The lower part of the mudstone units is generally silty or sandy and may be flaser-bedded. Thin sandstones dominated by ripple and small-scale trough cross-stratification are scattered throughout the mudstone facies. These sandstones have planar contacts and pinch out abruptly within the mudstone. Thick intervals of finely interbedded thin mudstones and sandstones are also common. Occasionally, these intervals can be traced laterally to the margins of one of the lens or sheet sandstones. Bivalves are abundant at the base of some thin sandstone units and the lower part of the John Henry Member contains thin coals and carbonaceous shales. The contact between the middle and basal parts of a sequence is gradational.

Deposition occurred primarily within anastomosing and meandering fluvial systems under conditions of high accommodation production.

The upper parts of these sequences consist of laterally extensive, multistoried sheet sandstones. Mudstone facies are generally thin and discontinuous or not present. Lower stories are typically finer grained than upper stories and consist mostly of trough cross-bedded sandstone. Trough cross-bedding may or may not grade upward into wavy and parallel laminations. Occasionally, lateral accretion surfaces can be seen in the lower stories. Upper stories typically consist of coarser sandstone and are trough to planar cross-bedded. Boundaries between stories are sharp and commonly display some erosional relief. The finer grained, trough cross-bedded sandstones with lateral accretion surfaces were deposited by meandering streams. Coarse-grained, trough to planar cross-bedded sandstones without lateral accretion surfaces were deposited mostly in sandy braided systems. These units represent a normal regression as the basin filled during a slowing in the production of accommodation space.

The capping part of each sequence is dominated by laterally extensive, multistoried sheets of trough and planar cross-stratified gravelly sandstone and sandy conglomerate. The tops of all stories within the sheet are sharp and show erosional relief of a few meters. The basal contact for the capping unit is sharp, but conformable, except for the Canaan Peak Formation, which consists of a cobble conglomerate at the base and locally overlies the Kaiparowits Formation with an angular unconformity. The capping parts of the sequences represent deposition by sandy to gravelly braided streams during a period of slow accommodation production.

Sequence Stratigraphic Models for the Kaiparowits Basin

Because basin subsidence and eustatic sea level rise each create an increase in accommodation

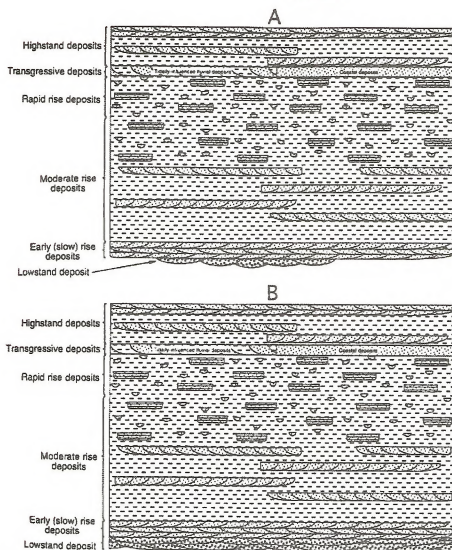


Figure 6. Response of fluvial systems to a eustatic sea level rise. A) An incised valley geometry at the base that forms under conditions of a sea level fall, which is faster than the rate of basin subsidence. B) A progradational sheet geometry at the base associated with a eustatic sea level fall, which was slower than associated basin subsidence rates.

lowering of eustatic sea level would then decrease the rate at which accommodation space is produced in these areas, resulting in a basinward progradation of the fluvial system, or possibly incision, depending on the relative rates of eustatic fall and basin subsidence. Fluvial architectural patterns would be controlled by rates and directions of base level change, which could be predicted by vertical position within the sequence (Figure 6). The overall succession would consist mostly of conformable sequences exhibiting alternating aggradational and progradational patterns (Mutti and Sgavetti, 1987; Jordan and Flemings, 1991).

Lowstand Deposits

A base level lowstand in foredeep basin continental deposits is characterized by either stream entrenchment and sediment bypass, producing an irregular regional unconformity (Figure 6A), or more likely, a basinward progradation of the fluvial system, depositing laterally extensive sandy and gravelly sheets with conformable and possibly intertonguing lower contacts (Figure 6B). In the case of incision, a thin lowstand fluvial deposit similar in character to the progradational sheets, but with incised valley-fill geometry, may be preserved above the unconformity as base level begins to rise. In either case, preserved overbank sediment is minimal due to extensive lateral migration and floodplain reworking.

Early (Slow) Base Level Rise

As base level begins to rise, sand sheets become stored. Streams continue to migrate back and forth, stacking one coarse-grained sheet upon another, resulting in minor aggradation. There may be discontinuous lenses of fine-grained overbank deposits preserved, but channel deposits continue to dominate the sequence.

Moderate Base Level Rise

An increase in the rate of base level rise causes sheets to become less extensive laterally due to a shorter migration time at a given base level. Channels no longer are able to rework



their entire floodplains, and the amount of preserved overbank sediment greatly increases. Greater preservation of overbank deposits results in enhanced channel stability and development of a meandering channel pattern. As channels become stabilized, the degree of lateral migration decreases while vertical stacking may increase, producing narrow, multistoried sandbodies encased in mudstone. Channel migration becomes more a result of avulsion than lateral erosion/accretion. These deposits show increasingly significant rates of vertical aggradation, principally within overbank facies.

Rapid Base Level Rise

A continued increase in rates of base level rise results in very rapid aggradation, producing anastomosed stream patterns in which isolated sandbodies are encased in mudstone. Lateral erosion/accretion becomes insignificant and migration is almost exclusively a result of avulsion. Overbank deposits dominate the sequence.

Transgressive Deposits

Rates of base level rise might become such that the fluvial system cannot provide enough sediment to fill the available space, resulting in a marine transgression. This would be marked by a transgressive disconformity as the surface of the fluvial deposits is reworked by advancing wave base. Thin transgressive coastal deposits may overlie the fluvial deposits. Slightly more inland, fluvial deposits might include features indicative of significant tidal influence (Shanley, 1991; Shanley and McCabe, 1991). Alluvial aggradation would shift landward to some location where rates of sediment input are balanced with rates of base level rise.

Highstand Deposits

Highstand deposits are characterized by laterally restricted sand sheets at the base with abundant associated overbank sediments, grading upward to laterally extensive, possibly multistoried, sand sheets with little preserved overbank material. This succession is produced as available accommodation space becomes filled during a base level highstand as the rate of eustatic rise slows and then turns to a

eustatic fall. Depending upon the relative rates of basin subsidence and eustatic base level fall, the upper boundary of the highstand deposits could be either a type 1 or a type 2 sequence boundary.

Tectonic Models

Traditionally, the progradation of coarse clastic deposits into foredeep basins has been related to active movement within the adjacent thrust belt (Armstrong and Oriol, 1965; Wiltchko and Dorr, 1983). This concept implies that source area uplift and associated basin subsidence result in greater relief between the source area and the basin, leading to higher erosion rates and therefore the widespread distribution of coarse-grained deposits. This idea has been challenged in recent years by a number of authors on the basis that the lag time between uplift and new sediment production is much greater than the lag time between uplift and basin subsidence, and therefore, the asymmetrical nature of a foredeep basin would result in the trapping of coarse sediment adjacent to the thrust belt (Heller et al., 1988; Steidtmann and Schmitt, 1988; Flemings and Jordan, 1989). This has led to the development of new models that associate very coarse deposits, located in a narrow belt adjacent to the thrust front, to active thrusting (synorogenic conglomerates), and widespread coarse clastic sheets to a basinward shift in accommodation potential following the cessation of tectonic movement as the thrust load is eroded and rebounds and the load is shifted basinward in the form of sediment loading. On a local scale, tectonically controlled sequences are similar to eustatically controlled sequences, and in many cases, it may not be possible to distinguish between the two without regional information (Figure 5).

Isostatic Rebound Model

The most common explanation for the reworking of syntectonic deposits during times of tectonic quiescence considers the role of isostatic adjustment in elevating the basin following the cessation of major tectonic activity as continued erosion decreases the thrust belt



load. This is the two-phase model proposed by Heller et al. (1988) (Figure 7).

- **Phase 1: Active Tectonism:** Uplift within the thrust belt leads to geologically instantaneous basin subsidence, and therefore a rise in relative base level. Near the thrust belt, coarse conglomerates are deposited, but are confined to a narrow strip along the active front. Farther basinward, an abrupt vertical change from relatively coarse-grained sediment to much finer sediment occurs in response to a rise in base level and trapping of coarse-grained sediment near to the thrust belt. Fluvial systems respond to the growth in accommodation space with rapid aggradation, producing deposits dominated by fine-grained sediment. Sandstones are confined to isolated

lenses or thin sheets scattered throughout the finer sediment. As tectonic activity slows, accommodation space is produced at a much lower rate, leading to a coarsening-upward sequence dominated by multistoried sand sheets at the top.

- **Phase 2: Tectonic Quiescence:** Erosion within the thrust belt leads to isostatic rebound of the thrust belt and areas of the basin adjacent to it. In response, synorogenic deposits are reworked and redistributed basinward. The result is a lowering of relative base level and deposition of a widespread clastic sheet into the basin. These sheets correlate to unconformities formed within the synorogenic deposits.

Thrust Propagation Model

The thrust propagation model is similar to the isostatic rebound model in that episodes of active tectonism are separated by periods of tectonic quiescence. The principal difference between these two models lies in the processes operating during the tectonically "quiet" phase and the amount of erosion that takes place within the earlier synorogenic deposits during this phase. Forward breaking thrust belts develop through formation of new thrusts in front of the old. The new thrust begins in the subsurface along a decollement surface and propagates basinward and upward from the decollement, leading to uplift in front of the older thrust belt (Figure 8). As in the isostatic rebound model, synorogenic sediments are reworked and deposited farther basinward. In the thrust propagation model, uplift may be sufficient to entirely rework the synorogenic deposits, leaving a record of only finer grained deposition adjacent to the thrust belt. The reworked sediments would then be carried basinward, resulting in coarse clastic sheets in the basin that have no coarse-grained equivalent in the area of the thrust belt.

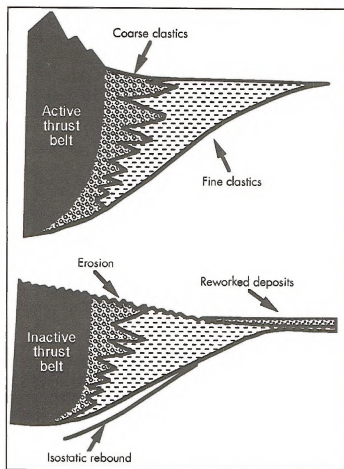


Figure 7. Isostatic rebound model. Coarse syntectonic deposits accumulate in narrow bands adjacent to the thrust belt during episodes of active tectonism. Due to isostatic rebound, the upper portions of these deposits are reworked basinward during periods of tectonic quiescence as the mountain belt is lowered by erosion (modified from Heller et al., 1988).

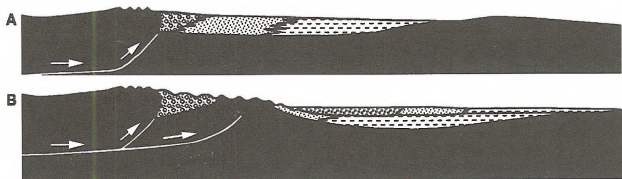


Figure 8. Thrust propagation model. A) Initial basin subsidence associated with thrusting. B) Subsequent frontal uplift associated with the development and propagation of a new thrust fault during tectonic quiescence.

Differentiating Between the Tectonic and Eustatic Models

Foredeep basins are created by flexural subsidence of the lithosphere beneath and in front of a tectonic load associated with thrust faulting and folding and synorogenic sedimentation. As such, tectonic activity exerts the primary control on foredeep basin geometry and stratal patterns. In proximal portions of the basin, subsidence and sedimentation rates are generally sufficient to preclude any significant influence by eustatic sea level variations. However, decreasing subsidence and lower sedimentation rates permit eustatic sea level fluctuations to strongly affect and even dominate depositional patterns away from the thrust belt. The stratigraphy of the Western Interior foredeep basin is represented by thick intervals of continental strata near the thrust belt that thin basinward and grade into shoreline sandstones at their distal ends, eventually pinching out into thick accumulations of marine mudstone. Thickness, aerial distribution, and composition of these continental facies, together with timing relationships to dated thrusting events and eustatic sea level curves, appear to be useful in determining the relative impact of tectonic and eustatic processes in the development of foredeep basin sequences.

Distribution and Geometry of Coarse Clastic Deposits

Eustatic Models

In a eustatically dominated sequence, coarse clastic deposits represent eustatic lowstands and may develop as either widespread progradational sheets or discontinuous valley fills. Progradational sheets form during a lowering of sea level in a setting where the rates of basin subsidence remain equal to or greater than the rates of sea level fall. Accommodation space continues to be generated in landward areas, but at a slower pace, allowing coarse sediment to be transported to more distant parts of the basin. These deposits would form continuous sheets from the thrust belt into the basin that become progressively finer grained basinward due to selective deposition of the largest particles and particle breakdown by weathering processes. A widespread clastic deposit associated with lowstand progradation would therefore constitute part of a thick conformable succession of coarse conglomerate near the thrust belt that thins and grades basinward into a sheet of sandy conglomerate and gravelly sandstone bound conformably above and below by relatively thick intervals of finer-grained fluvial deposits (Figure 9A). The lower contact will step progressively basinward during a period of base level lowering and then step landward as base level subsequently rises.

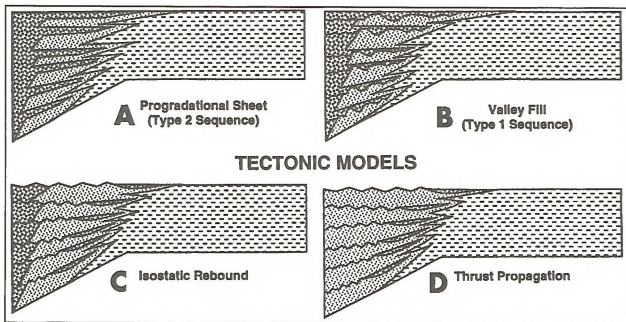


Figure 9. Progradational sheets are associated with type 2 eustatic lowstands and produce thick, conformable successions of coarse-grained deposits that fine basinward. Valley fill deposits form during type 1 eustatic lowstands and consist of laterally discontinuous coarse-grained units separated from underlying beds by unconformities. Isostatic rebound creates a thick succession of unconformity-bound syntectonic units near the thrust belt and isolated coarse sheets farther basinward with little or no physical contact between the two. Thrust propagation produces a succession similar to that of isostatic rebound but allows for the potential complete removal of syntectonic deposits.

Valley fill deposits form in settings where the rate of sea level fall is greater than the rate of subsidence, leading to channel incision and development of an irregular erosional surface. As base level subsequently rises, accommodation space is created in progressively more landward areas, trapping coarse sediment within the incised channels. Therefore, valley fill deposits develop a number of time-equivalent, laterally discontinuous, linear or ribbon-shaped bodies of backstepping gravely deposits that grade landward into thick successions of unconformity-bound conglomerate beds (Figure 9B). A sheet-like geometry would form only if the valleys became completely filled and streams then spread sediment over surfaces separating adjacent valleys (Figure 10). Incision can also be produced by tectonic uplift, but in many cases, may be distinguished from a eustatic fall by angular discordance between the eroded units and the valley fill deposit. Reflecting the relative direction of base level movement, lowstand progradational sheets would tend to coarsen upward as the rate of space creation diminished and finer grained sediments were transported through

the system, whereas the valley fill deposit would fine upward as accommodation potential increased.

Tectonic Models

According to both the isostatic rebound and thrust propagation models, coarse synorogenic conglomerates are reworked from areas of the foredeep basin proximal to the thrust belt and then redistributed into the basin as coarse clastic sheets during periods of post-orogenic quiescence (Figures 9C and 9D). Isostatic rebound would necessarily leave a portion of the original synorogenic deposit near the thrust belt, unless the amount of rebound were greater than the amount of original subsidence, which is highly unlikely. This would lead to a thick succession of unconformity-bound conglomeratic bodies near the thrust belt and widespread gravely sheets farther basinward with the potential for little or no physical connection between the two. Isostatic rebound and fault propagation both lead to a lowering of base level ahead of the advancing clastic deposit. Redistribution of coarse clastics over this surface will produce a sheetlike rock

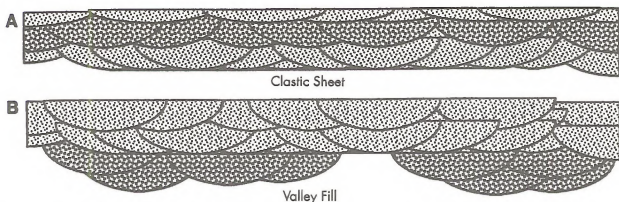


Figure 10. A) Lawstand progradational sheets have a tabular geometry and coarsen upward as base level falls. A thin, finer grained interval may form at the top during a subsequent base-level rise. Lower contacts are gradational. B) Valley fill deposits have incised lower contacts forming valleys that must be filled before coarse-grained sediment can spread out over wide areas. Valley fill deposits fine upward in response to a rising base level. Tectonically redistributed postorogenic sheets are similar in geometry to lawstand progradational sheets (A), but lower contacts are sharp and may show some scouring.

body similar to that of a eustatic lowstand progradational sheet, but with sharper lower contacts (Figure 10). The lower contact would most likely show some scouring associated with fluvial channel migration, but probably would not appear as a major unconformity. Timewise, the gravely sheets would correlate to the unconformities separating syntectonic conglomerates. The thrust propagation model provides a mechanism for generating much higher amounts of uplift through the development of a new thrust sheet in front of the old. The syntectonic deposit could potentially be reworked entirely, leaving little or no record of the original conglomerate. This would result in a coarse clastic sheet, which is not physically connected to the thrust belt, but which instead correlates to an unconformity in finer grained deposits of that area. Successive sheets in either model should step basinward and become progressively coarser grained as the axis of subsidence shifts basinward through subsequent thrusting events.

Application to the Kaiparowits Basin

Eaton and Nations (1991) have produced a restored cross section for Upper Cretaceous strata in southwestern and south-central Utah (Figure 11). This cross section shows that most coarse-grained units in the Kaiparowits Basin, including the Calico Bed, the Drip Tank Member, the capping sandstone member of

the Wahweap Formation, and the Canaan Peak Formation, are not traceable back to the thrust belt. Additionally, conglomeratic units of the Kaiparowits Basin show a basinward stepping trend through time, and each successive sheet is coarser grained and thicker than the previous. These relations suggest that coarse-grained clastic units capping the stratigraphic sequences of the Kaiparowits Basin are primarily the result of the development and initial movement on thrust faults to the west.

Coarse clastic deposits in the Kaiparowits Basin are in the form of laterally extensive sheets with sharp lower and upper boundaries. The basal contacts are typically scoured and have been interpreted by some workers as major unconformities (Shanley, 1991; Shanley and McCabe, 1991), but the planar nature of the contacts, a lack of angular discordance between units above and below, and a lack of evidence for major gaps in time suggest that the scouring is related to normal fluvial processes operating during deposition of the gravel sheets. Additionally, the coarse clastic deposits of the Kaiparowits Basin all thicken to the northwest toward the thrust belt. The sheetlike geometry of these deposits could be used to support either a eustatic lowstand progradation or postorogenic quiescence; however, I believe the sharp lower contacts favor the tectonic interpretation. If the

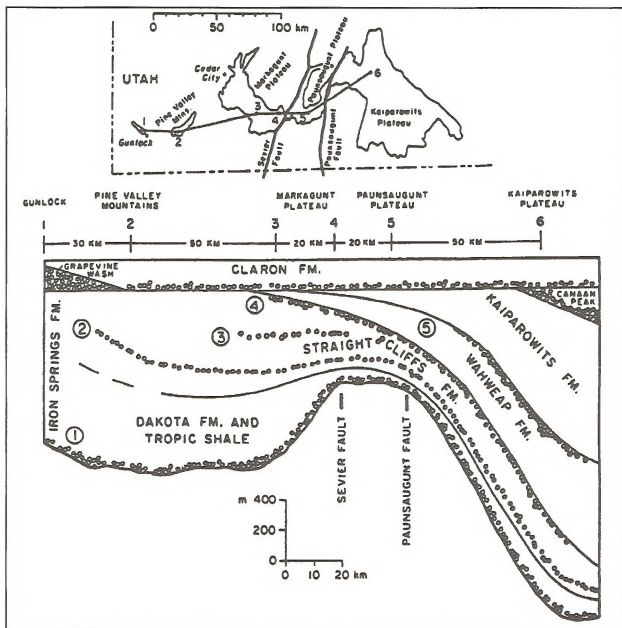


Figure 11. Prominent coarse clastic deposits present in the Kaiparowits Basin are either absent or are poorly developed adjacent to the thrust belt (Gunlock area). These deposits also step progressively basinward (from Eaton and Notions, 1991).

lowstand sea level remained fixed at one elevation for a long period of time and there was no additional subsidence during this period of time, it would be possible to form a sharp contact at the base of the lowstand progradational sheet through repeated channel migration across the area. However, that would require that aggradation take place during the subsequent transgression rather than during the lowstand. Transgressive deposits for most basins are typically thin and transgression shifts the focus of fluvial sedimentation landward. The units capping sequences in the Kaiparowits

Basin all prograde far into the basin, and with the exception of the Calico Bed, all reach thicknesses in excess of 100 m. The Calico Bed can be as thick as 50 m (Bobb, 1991). Sharp lower contacts, great thickness, and widespread basinward distribution all support simultaneous progradation and aggradation during periods of slow basin subsidence.

Paleocurrent Orientation

In asymmetrical basins, fluvial channels migrate toward the location of maximum



subsidence (Alexander and Leeder, 1987). Crustal loading by thrust faults depresses the lithosphere immediately adjacent to the thrust front, creating a linear trough. Major drainage systems then flow parallel to the thrust front along the axis of maximum subsidence. During periods of tectonic quiescence and relatively slow subsidence, it may be possible for the proximal portion of the foredeep basin to become overfilled, producing a basinward gradient and permitting streams to flow away from the thrust belt. Such a gradient would likely exist if space creation were dominated by eustatic processes. Therefore eustatic dominance would most likely be characterized by overfilled basins with fluvial systems that flow away from the thrust belt, whereas tectonic dominance would be shown by thrust parallel fluvial systems. In a tectonically generated sequence, subsidence rates could remain high enough during the postorogenic portion of the cycle to prevent overfilling and maintain the axial system. In the Kaiparowits Basin, Gustason (1989) reported alternating episodes of thrust parallel- and thrust perpendicular-flowing fluvial systems for the Dakota Formation and related this to alternating intervals of tectonic activity and quiescence, respectively. For the units involved in this study, the upper Straight Cliffs through Kaiparowits Formations, no such pattern was found. Rather, streams flowed predominantly

to the northeast throughout the section, again suggesting tectonic dominance in their formation.

Timing

Thick stratigraphic sequences for the Kaiparowits Basin have been broadly correlated in time to the second-order eustatic cycles of Kauffman (1977, 1985; Kauffman and Caldwell, 1993) (Figure 2), yet these sequences are interpreted here to have been driven primarily, and for Clagget and Bearpaw equivalents entirely, by tectonic processes. A similar relationship was noted by Villien (1984) for age-equivalent strata in the Wasatch Plateau and San Rafael Swell areas, where he correlated thrusting events from the Sevier orogenic belt to both the foredeep stratigraphic record and the eustatic sea level curve for the Cretaceous Western Interior Basin. He found that in central Utah, both transgressions and synorogenic conglomerates correlate to episodes of active thrusting, whereas regressions and widespread clastic sheets correspond to periods of postorogenic quiescence (Figure 12). These findings are in agreement with those of Kauffman (1984, 1985) for Cretaceous-age strata from the Utah-Arizona and Wyoming-Montana-Idaho regions of the Western Interior in which episodes of thrust emplacement, basin subsidence, and explosive volcanism have been tied to rises in

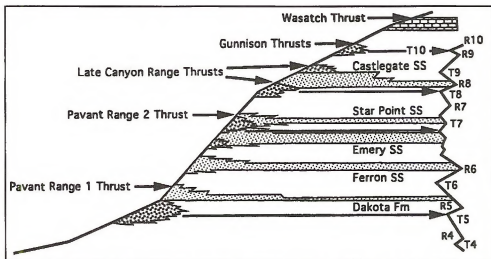


Figure 12. In central Utah, synorogenic conglomerates have been correlated to eustatic transgressions and widespread clastic sheets have been tied to eustatic regressions. Arrows indicate the end of thrusting for specific thrust faults west of the Wasatch Plateau (modified from Villien and Kilgfield, 1986).



base level and coastal transgression, whereas tectonic quiescence corresponds to base level fall and coastal regression (Figure 13). Additionally, these events have been tied to global seafloor spreading rates and eustatic cycles (Kauffman, 1984, 1985; Kauffman and Caldwell, 1993). Thus it appears that development of accommodation space in the distal foredeep basin by tectonic and eustatic processes and in the proximal portion of the basin by tectonic processes alone should be related in time. Correlations with specific thrusting events have not been made for continental strata of the Kaiparowits Basin; however, it appears that several of the thrust faults affecting central Utah are the same as those affecting the Kaiparowits region, such as the Wah Wah/Mineral Range/Canyon Range system and the Blue Mountain/Pavant system (Figure 1).

Conclusions

Upper Cretaceous sequences of the Kaiparowits Basin most closely fit the thrust propagation tectonic model and developed in association with the eastward advance of the Sevier thrust belt and adjacent foredeep basin based on the following evidence: 1) coarse-grained units thicken toward the thrust belt but are not traceable back to that region, 2) coarse clastic deposits are thick with sharp, planar lower and upper contacts and have a sheet geometry, 3) coarse clastic units show a basinward stepping trend through time and each successive sheet is coarser grained and thicker than the previous sheet, 4) paleocurrent orientations indicate a predominantly northeast flow throughout the section, suggesting asymmetric basin subsidence parallel to the thrust front, 5) transgressions and synorogenic conglomerates in the Uinta Basin of central Utah have been correlated to

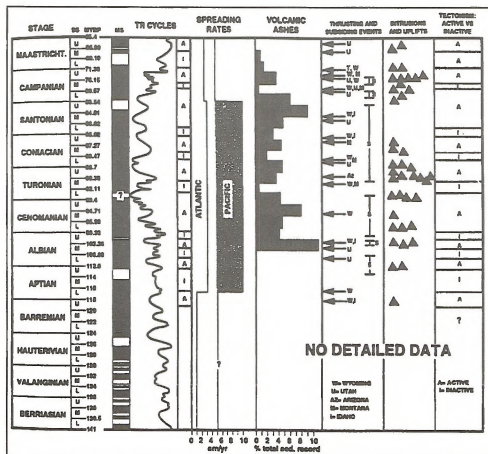


Figure 13. Timing relationships between sea level fluctuations, volcanic intensity, thrusting events, and subsidence events of the Western Interior Basin as related to global magnetostratigraphy and sea-floor spreading rates (from Kauffman and Caldwell, 1993).



episodes of active thrusting, whereas regressions and widespread clastic wedges correspond to periods of postorogenic quiescence; several of the thrust faults affecting central Utah are the same as those affecting the Kaiparowits region suggesting a similar relationship, and 6) significant influence by marine processes diminishes upward through the Upper Cretaceous succession of the Kaiparowits Basin.

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The Grand Staircase-Escalante National Monument: An Ideal Site to Monitor Climate Variability and Change

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Modern and Paleoecological Resources within the Monument

Understanding how long-term environmental processes operate and interact is essential for making informed management decisions. Halvorson and Davis (1996) state that "(t)he only way for park administrators to evaluate the status of the natural resources in the national parks and to know how to manage these resources is to develop a systematic

ABSTRACT

■ The Grand Staircase Escalante National Monument (GSENM) offers an unparalleled opportunity for documenting and understanding the dynamics of environmental and climatic change. First, the GSENM occupies a climate-sensitive area located at the intersection of two climatic boundaries; second, the Monument spans five vegetation zones across an elevational gradient; and third, its arid environment preserves evidence of past floral, faunal, archaeological, and geological processes. This unique combination of location, vegetative zones, and climate provides an excellent record of past climate and environments. By monitoring the modern climate, flora, and fauna, and coupling this information with the paleoenvironmental record using a Geographical Information System (GIS), the impact of future climate variability and change on hydrology, geology, vegetation, wildlife, and cultural resources may be estimated. A more thorough understanding of the sensitivity of ecosystem response to climate change will help managers to develop strategies to manage and preserve a unique and sensitive resource for future generations.

monitoring program and to conduct research on the most important processes that control these ecosystems. Such monitoring and research programs yield information that can be used to protect the parks and to guide management decisions that will preserve the natural resources."

The Grand Staircase Escalante National Monument (GSENM) offers an unparalleled opportunity for documenting and understanding the dynamics of environmental processes and their effects on plant, animal, and human populations for three reasons.

First, the GSENM occupies a climate-sensitive area. Presently, the GSENM is located at the intersection of two climate boundaries; it is



affected by winter storms originating in the Pacific Ocean and by summer storms originating in the Gulf of Mexico. The strength and paths of these atmospheric circulation patterns have varied over time, causing distinctly different environmental responses. For example, the environmental response to changes in these patterns is reflected in current and past distributions of vegetation, fauna, geomorphic events, and human history.

Second, the GSENM spans five vegetation zones (Figure 1). The plants, animals, and humans occupying the diverse habitats along this elevational gradient can all provide a long-term record of response to climate change. For example, a northward shift of summer rainfall (strengthening of the summer storm pattern) can result in an increase or decrease in the spatial/elevational extent of certain taxa. Plant materials from packrat middens and pollen sequences in sediments can record this shift. When many such records are available, the movements of individual plant species through tens of thousands of years can be reconstructed. Additionally, past climate can be estimated using the modern analog climate parameters of different plant taxa. Thus, the record in the GSENM has the potential to reconstruct past

environments and lend insight into predicting future environmental effects resulting from global warming.

Third, the GSENM is arid. The evidence for past floral, faunal, archaeological, and geological processes is well-preserved in arid localities for thousands of years. The canyons of the Colorado River and its tributaries are ideal for the reconstruction of past floods. Canyon cross sections and flood stratigraphy can be combined with hydraulic modeling to reconstruct the magnitude and frequency of extreme floods that have occurred over the past hundreds to thousands of years. Reconstructed chronologies of extreme floods can be compared to a large variety of proxy paleoclimatic data (tree-ring series, pollen records, and plant macrofossils) to evaluate linkages between climatic variability and the magnitude and frequency of large floods. Single-site and regional paleoflood records can be used to evaluate or improve regional flood-frequency models and to determine the maximum regional flood potential. The degree of preservation associated with arid environments facilitates a more precise analysis of climate, ecological trends, and patterns.

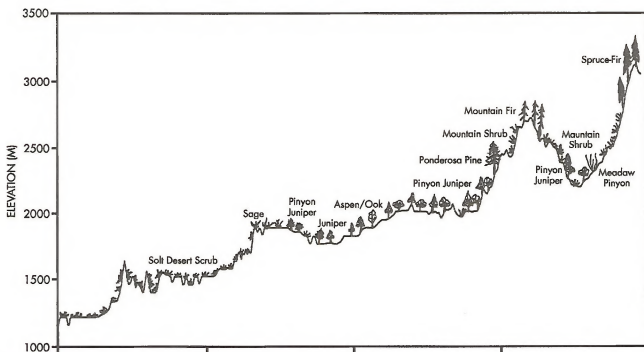


Figure 1. Elevational transect showing vegetation zones.



A Geographic Information System (GIS) can be used to analyze the above patterns, relationships, and trends by visually linking paleoecological and modern environmental data sets to provide new insight into diverse management issues. For example, a long-term picture of landscape response to climate variation can provide baseline data to help land managers differentiate between human- and climate-induced landscape change. One example would be the potentially destabilizing effects of human populations on sensitive habitats. Although the reality and possible causes of abandonment in portions of the Southwest in the 12th or 13th century are still unclear, it may have been due to local drought (Larson and Michaelsen, 1990) or to periods of larger and more frequent flooding (Enzel et al., 1994) affecting the region. Such floods may have been due in part to human-induced deforestation or intentional fires. Predictive modeling of archaeological site distribution can be achieved through the examination of paleoclimate and geomorphological data, and results of archaeological investigations can be integrated into a comprehensive study of the effect of human use of the landscape.

The establishment of a long-term record of environmental change and human history may identify situations where past landscape response was similar to modern times and serve as an analog for future change. A long-term record may also provide a scale to put such changes into perspective. A history of ecosystem variation will also establish a baseline data set so that management decisions can be formed and justified on the basis of sound, scientific research.

Implications

Based on paleoclimatological proxy evidence, it is highly likely that the present climatic conditions will change dramatically in the future. In addition to natural climate change, anthropogenic impacts on the Earth's atmosphere may also change the climate. With doubled atmospheric CO₂ concentrations,

global warming estimates for south-central Utah show January and July temperatures 3-4 °C warmer than today with decreased January precipitation and strongly suppressed July precipitation compared to modern measurements (Gorgi et al., 1994).

Whether we are on the verge of severe global warming or not, the inevitability of climate variability and change will result in corresponding changes in the environment. Modern climate monitoring will provide essential time-series climatic information. Spatially distributed climate stations will facilitate Monument development planning, ongoing Monument management, climate warning systems, and global change impact assessment.

Summary

Because of its unique combination of location, vegetative zones, and climate, the GSENM can provide a record of past ecology that can help us to understand how future climate change may impact hydrology, geology, vegetation, wildlife, cultural resources, and visitor appreciation. By monitoring the modern climate, flora, and fauna, and coupling this information with the paleoenvironmental record using a Geographical Information System (GIS), we can better understand how quickly, and under what conditions, ecosystems in the GSENM and surrounding area could immediately and significantly respond to future climate perturbations. A more thorough understanding of the sensitivity of ecosystem response to climate change will help managers to develop strategies to manage and preserve a unique and sensitive resource for future generations.

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Digital GIS Geologic Mapping of the Grand Staircase-Escalante National Monument

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ABSTRACT

■ The Utah Geological Survey (UGS) began production of a digital geographic information system (GIS) 1:100,000-scale geologic map of part of the Grand Staircase-Escalante National Monument in July 1996, before the Monument was designated. The map was started in response to the need for a digital geologic map for land management issues in conjunction with the planned Andalex coal mine. After designation of the Monument, the UGS immediately expanded the planned map area to produce a geologic map of the entire Monument. About one-half of this map was completed and released in July 1997. The remaining one-half will be completed by July 1998.

The UGS is creating the map by compiling published and new field maps. Most of the Monument is covered by approximately 50 geologic maps published between 1952 and 1990 that have various scales, emphases, and detail. New field mapping fills in areas that are not mapped in sufficient detail and resolves border discrepancies between maps of different detail or scale.

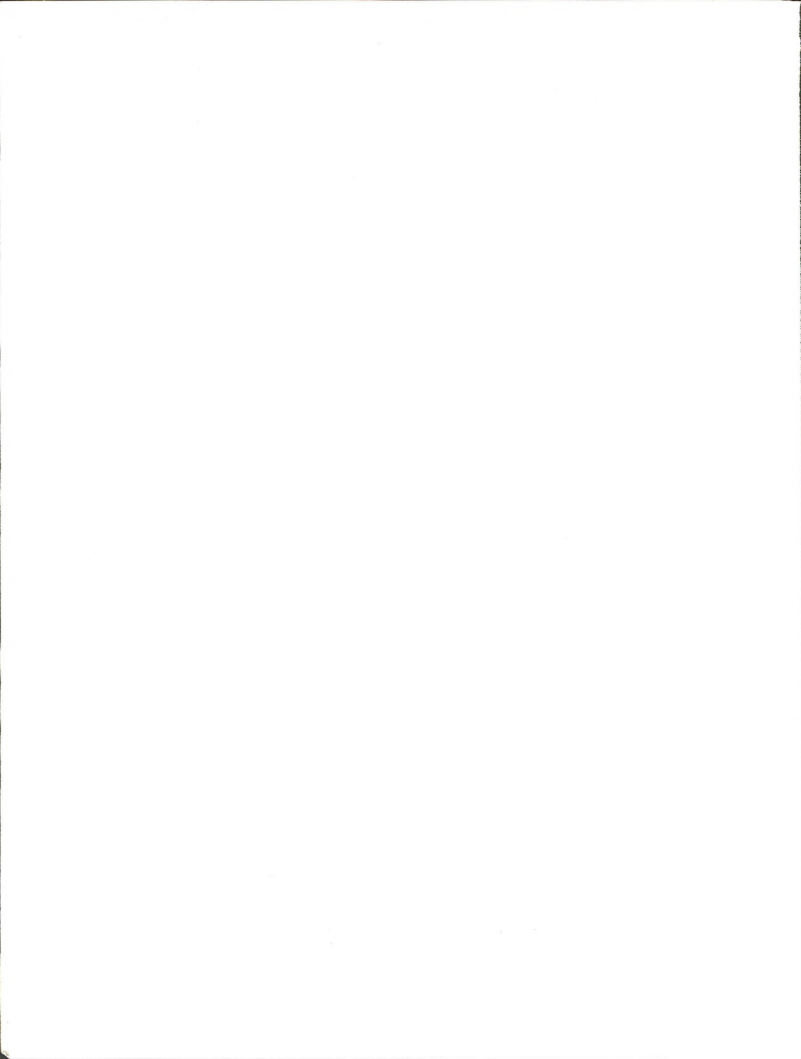
The intermediate detail 1:100,000-scale map provides advantages of both smaller scale regional maps and larger scale local maps. The single map of the Monument will extend well beyond the Monument border, providing the "big picture." However, the map is detailed enough to show all geologic formations in the Monument; most member subdivisions; approximately 20 subdivisions of surficial deposits; most faults, anticlines, synclines, and monoclines; and most major geology-related economic resources. It does not show most individual drill holes, mines, or prospects, or surficial deposits that are thin or only cover a few tens of acres or less.

Since geologic features were identified as a major reason for establishing the Monument, the map will be an integral tool in developing and carrying out a management plan. The geology of the Monument is highly variable, with a large number of distinct but interrelated features ranging from folds and faults to economic deposits and paleontologic resources. A GIS map allows the manager or planner to focus on a single area or geologic feature, or to compare several areas or features to assure that all aspects of the geology are considered in their proper framework.



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